ERDC/CERL SR-14-8

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Base Facilities Environmental Quality

Forest Microclimate Characteristics Review

An Annotated Bibliography

Rosemary Keane, Hannah Pitstick, Patrick J. Guertin, and Dick L. Gebhart

September 2014

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Construction Engineering Research Laboratory
U.S. Army Engineer Research and Development Center
2902 Newmark Drive
Champaign, IL 61822

Final report

Prepared for Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT))
1400 Defense Pentagon
Washington, DC 20314-1000

Under P2 Project #335114, "Prediction and Adaptation of Military Natural Infrastructure in Response to Climate Change: Forest Modeling"

Abstract

The U.S. Army owns many acres of forested training lands. Management of these forest lands can impact the Army's ability to meet training goals as these lands have implications to noise mitigation and threatened and endangered species populations. To support the need to manage these forested areas, the Environmental Processes Branch of the US Army Engineer Research and Development's Construction Engineering Research Laboratory conducts ongoing studies of forest lands, including the possible implications of climate change on forests. An important subtopic of that study is the microclimate a forest creates under and within its canopy; a forest microclimate can affect a wide variety of factors within the forest including how sound travels, vegetation regeneration, and faunal interactions. This report supports that important subtopic by creating an annotated bibliography of works related to how microclimates varied within forests and how they impacted environmental components within the forest. The resulting information will provide insight on how to design future work to capture relevant data and how to interpret those results.

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Preface

This study was conducted for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) under Research, Development, Test, and Evaluation Program Element A896, “Base Facilities Environmental Quality” (appropriation 21 2020 622720896) as P2 Project #335114, “Prediction and Adaptation of Military Natural Infrastructure in Response to Climate Change: Forest Modeling.” Technical monitors were Lorri A. Schwartz and Richard G. White at Headquarters Department of Army, Assistant Chief of Staff for Installation Management (HQDA ACSIM).

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CN), U.S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Dr. Imee Smith was Acting Chief, CEERD-CN-N; Ms. Michelle Hanson was Chief, CEERD-CN; and Mr. Alan Anderson was the Technical Director for Military Ranges and Lands. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Ilker Adiguzel.

COL Jeffrey R. Eckstein was the Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
hectares	1.0 E+04	square meters

Abbreviations

Term	Meaning
AEI	area of edge influences
ANOVA	analysis of variance
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics, and Tchnology
BA	basal area
CN	Installations Division of ERDC-CERL
CN-N	Ecological Processes Branch at ERDC-CERL
CO_2	carbon dioxide
D-AEI	delineating area of edge influences
DEI	depth of edge influence
ERDC-CERL	Engineer Research and Development Center-Construction Engineering Research Laboratory
ha	hectare
K	Kelvin
km	kilometer
m	meter
N	nitrogen
PAR	photosynthetically available radiation
PPFD	photosynthetic photon flux density
SEI	significance of edge influence
S	sulfur
SO4	sulfate
TES	threatened and endangered species
VPD	vapor pressure deficit

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1 Introduction

1.1 Background

A primary mission of the Engineering Research and Development Center – Construction Engineering Research Laboratories (ERDC-CERL) is to conduct research in support of sustainable Army Installations. ERDC-CERL's Environmental Processes Branch (CN-N) is tasked with activities focused on natural resources issues including compliance and developing technologies to support sustainability on non-cantonment lands (e.g., maneuver areas, weapons ranges).

Past and current research areas of CN-N include a variety of efforts to study forest lands as related to their importance in noise mitigation for Army training and providing habitats for threatened and endangered species (TES). Areas of study include forested lands today with the possible future implications of climate change. An important and relevant subtopic is the impact a forest has in terms of the microclimate it creates under and within its canopy. The forest microclimate affects a wide variety of important factors within the forest including how sound travels, vegetation regeneration, and faunal interactions.

To support this area of CN-N focus, researchers conducted literature reviews on how microclimates varied within forests when compared to the surrounding environment as well as how any differences impacted components of the environment within the forest (e.g., air temperature, humidity, soil temperature). The resulting information is valuable for several reasons including providing insight into study designs to capture relevant installation forest data and interpreting other forest study results.

1.2 Objective

To support past and ongoing research efforts, this work summarized 92 journal articles pertaining to forest microclimate by producing an annotated bibliography.

1.3 Approach

The general approach followed when compiling the literature selected for this document was a library search using Biosis Previews© and similar bib-

liographic database services, followed by acquisition of the publication, then review and documentation of the publication. This work covers journal articles published from the late 1960s to 2013.

Each annotation consists of a reference citation, followed by a paragraph highlighting the important ideas presented, then a list of variable(s) contained in the study. Annotations of the publications are organized into three chapters based on the geographical area where the majority of the study occurred: United States, Canada, and other international countries.

A summary chapter precedes the annotation chapters. In the summary chapter, key information (author, year, title, and variables) is presented in tabular format to provide a convenient summary of studies covered by this work. The summary tables also give a page number reference to the full annotation within this report.

2 Summary of Studies by Area

A total of 92 references were selected for annotation, and they are summarized in the subsections below according to the three broad areas in which each study took place – United States, Canada, and other international countries. Actual annotations are again separated by the same three broad areas and appear in Chapters 3, 4, and 5.

For a complete list of all references given alphabetically by author, please refer to the reference list beginning on page 73.

2.1 Summary of U.S. studies

Table 1 lists the 41 selected studies that occurred in areas of the United States, listed in alphabetical order by last name of the study's first author. Annotations for these references are in Chapter 3. Hyperlinked page number and lists of study variables are also given in Table 1 for easy referral to each study from this summary.

Table 1. Summary of selected studies in the United States.

First Author	Year	Title	State	Variables	Page for Annot.
Allen	1968	Turbulence and Wind Speed Spectra within a Japanese Larch Plantation	New York	turbulence, tree height, needle fall, wind flow	15
Brown	1969	Characterization of Forest Vegetation Analogs	n/a*	roughness, diffusion, vertical transfer rate, closure, canopy density	15
Cadenasso	1997	Functional Location of Forest Edges: Gradients of Multiple Physical Factors	New York	maximum, minimum, and solar noon air temperatures; relative humidity, photosynthetically available radiation; soil temperature; soil moisture; and soil depth	16
Canham	1990	Light Regimes beneath Closed Canopies and Tree-Fall Gaps in Temperate and Tropical Forests	Ohio, eastern United States, Costa Rica	photosynthetically available radiation, photosynthetic photon flux density, canopy gaps	17

First Author	Year	Title	State	Variables	Page for Annot.
Chen	1993a	An Empirical Model for Predicting Diurnal Air-Temperature Gradients from Edge into Old-Growth Douglas-Fir Forest	Washington, Oregon	air temperature maximum, minimum, and average	17
Chen	1993b	Contrasting Microclimates Among Clearcut, Edge and Interior of Old-Growth Douglas-Fir Forest	Washington, Oregon	air temperature, air moisture, soil temperature, soil moisture, short-wave radiation, wind velocity as a function of edge effects	18
Chen	1995	Growing-Season Microclimatic Gradients from Clearcut Edges into Old-Growth Douglas-Fir Forests	Washington, Oregon	air temperature, soil temperature, relative humidity, short-wave radiation, wind speed, significance of edge influence and depth of edge influence	19
Donato	2012	Multiple Successional Pathways and Precocity in Forest Development: Can Some Forests Be Born Complex?	n/a	Canopy cover, species diversity, gap and edge measures, species composition, solar radiation, light intensity	19
Dovciak	2010	Forest Management Changes Microclimate and Bryophyte Communities in the Cascade Mountains of Western Washington.	Washington	Air temperature, solar radiation, bryophyte diversity and abundance, and substrate quality	20
Els	2010	Changes in Forest Understory Associated with *Juniperus* Encroachment in Oklahoma, USA	Oklahoma	*Juniperus virginiana* cover, midstory development; photosynthetic photon flux density (PPFD), vegetation levels, litter, light, proximity to trunks	20
Euskirchen	2001	Effects of Edges on Plant Communities in a Managed Landscape in Northern Wisconsin	Wisconsin	vegetation gradient, differences in forest types, species richness, vegetation edge to interior gradient	21
Franklin	1987	Creating Landscape Patterns by Forest Cutting: Ecological Consequences and Principles	Pacific Northwest region	patch size, patch-clearing methods	22

First Author	Year	Title	State	Variables	Page for Annot.
Fraver	1994	Vegetation Responses along Edge-to-Interior Gradients in the Mixed Hardwood Forests of the Roanoke River Basin, North Carolina	North Carolina	percentage cover of individual species, percentage cover of exotic species, species richness, changes in plant cover along the gradient, changes in plant densities along the gradient, changes in overall plant species composition along the gradient	22
Gehlhausen	2000	Vegetation and Microclimatic Edge Effects in Two Mixed-Mesophytic Forest Fragments	Illinois	relative humidity, CO2 concentration, air temperature, soil temperature, soil moisture, and percentage canopy openness	23
Grady	2006	Influences of Thinning, Prescribed Burning, and Wildfire on Soil Processes and Properties in Southwestern Ponderosa Pine Forests: A Retrospective Study	Arizona	nitrogen, oxygen, mineralization, microclimate's effect on microbial activity	p. 24
Gray	2002	Microclimatic and Soil Moisture Responses to Gap Formation in Coastal Douglas-Fir Forests	Pacific Northwest region	solar radiation, soil and air temperature, soil moisture, canopy openness, volumetric soil content, and moisture in organic substrates	24
Halpern	2012	Level and Pattern of Overstory Retention Interact to Shape Long-Term Responses of Understories to Timber Harvest.	general United States	Retention percentages, solar radiation, understory diversity, ambient temperatures	25
Halpern	2013	Canopy Closure Exerts Weak Controls on Understory Dynamics	general United States	Solar radiation, species diversity, canopy cover, temperature, stem density	25
Heithecker	2007	Edge-Related Gradients in Microclimate in Forest Aggregates Following Structural Retention Harvests in Western Washington	Washington	light, air temperature, soil temperature, and soil moisture	26

First Author	Year	Title	State	Variables	Page for Annot.
Hibbs	1982	Gap Dynamics in a Hemlock-Hardwood Forest	Massachusetts	hemlock, regeneration, canopy gaps	27
Laurance	1991	Predicting the Impacts of Edge Effects in Fragment Habitats	Idaho	(necessary for the model) perimeter, area, size, shape index	27
Lutz	2012	Ecological Importance of Large-Diameter Trees	n/a	Canopy cover, biomass, solar radiation, climate variables, species composition, species diversity	28
Matlack	1993	Microenvironment Variation within and among Forest Edge Sites in the Eastern United States	Eastern United States	vapor pressure deficit, temperature, litter moisture, direct beam radiation	28
Matlack	1994	Vegetation Dynamics of the Forest Edge — Trends in Space and Successional Time	Pennsylvania and Delaware	vegetation flux, microclimate gradients as they relate to vegetation	29
Meyer	2001	Microclimatic Changes Induced by Ecological Restoration of Ponderosa Pine Forests in Northern Arizona	Arizona	light intensity, air temperature, and vapor pressure deficit	30
Morgan	2007	Canopy Characteristics and Growth Rates of Ponderosa Pine and Douglas-Fir at Long-Established Forest Edges	Idaho	leaf area, crown depth, basal area growth rate, sapwood area, proximity to forest edge	31
Neill	2013	Managing for Adaptive Capacity: Thinning Improves Food Availability for Wildlife and Insect Pollinators under Climate Change Conditions	Oregon	Canopy cover, species composition, light penetration, species diversity	31
O’Neal	2010	A Field-Based Model of the Effects of Landcover Changes on Daytime Summer Temperatures in the Northern Cascades	Washington	Canopy cover, soil temperature, stem density, surface temperatures	32

First Author	Year	Title	State	Variables	Page for Annot.
Palik	1990	Disturbance Versus Edge Effects in a Sugar Maple/Beech Forest Fragments	Michigan	vegetation gradient, compositional gradient, structural gradient	32
Powers	2008	Physiological Performance of Three Pine Species Provide Evidence for Gap Partitioning	Minnesota	light availability, gap partitioning, carbon assimilation, transpiration, water-use efficiency	33
Rambo	2009	Canopy Microclimate Response to Pattern and Density of Thinning in a Sierra Nevada Forest	California	air temperature, humidity, overstory density, understory density, height from forest floor	33
Raynor	1971	Wind and Temperature Structure in a Coniferous Forest and a Contiguous Field	New York	wind speed, temperature, tree height, canopy cover	34
Saunders	1999	Modeling Temperature Gradients Across Edges Over Time in a Managed Landscape	Wisconsin	temperature	34
Singer	1953	Relation of Gustiness to Other Meteorological Parameters	New York	gustiness, lapse rate, solar radiation, turbulence, wind speed	35
Spies	1994	Dynamics and Patterns of a Managed Coniferous Forest Landscape in Oregon	Oregon	forest interior, total interior area, edge area	35
Swanson	2011	The Forgotten Stage of Forest Succession: Early-Successional Ecosystems on Forest Sites	n/a	Solar radiation, soil temperature. canopy cover, species diversity, nutrient cycling	36
Thomas	2011	Variability of Sub-Canopy Flow, Temperature, and Advection in Moderately Complex Terrain	Oregon	wind structure, temperature, advection, subcanopy	36
Wales	1972	Vegetation Analysis of North and South Edges in a Mature Oak-Hickory Forest	New Jersey	vegetation gradients, vegetational transitions, microclimate variables relative to vegetation gradients	37

First Author	Year	Title	State	Variables	Page for Annot.
Weathers	2001	Forest Edges as Nutrient and Pollutant Concentrators: Potential Synergisms between Fragmentation, Forest Canopies, and the Atmosphere	New York	nutrients, pollution, soil retention	37
Wicklein	2012	Edge Effects on Saplings and Microclimate in a Small Temperate Deciduous Forest Fragment	Indiana	Soil moisture, soil chemistry, solar radiation, temperature, canopy cover, species composition, species diversity, stem density	38
Xu	2004	Scale-Dependent Relationships between Landscape Structure and Microclimate	Missouri	air temperature, soil temperature, soil surface temperature, diurnal temperature range of the aforementioned variables, gravimetric soil moisture, elevation, slope, canopy coverage	39
*n/a = study where specific location was not known or applicable.					

2.2 Summary of Canadian studies

Table 2 lists the five selected studies that occurred in areas of Canada, listed in alphabetical order by last name of the study's first author. Annotations for these references are presented in Chapter 4. Hyperlinked page numbers and lists of study variables are also given in Table 2 for easy referral to each study from this summary.

Table 2. Summary of selected studies in Canada.

First Author	Year	Title	Province	Variables	Page for Annot.
Bradley	2008	The Effects of Partial Harvest on the Understory Vegetation of Southern Ontario Woodlands	Ontario	level of harvesting, amount of weedy species, vegetation communities, past management, disturbance history, canopy cover	40

First Author	Year	Title	Province	Variables	Page for Annot.
Carlson	1997	Microclimate of Clear-Cut, Forest Interior, and Small Openings in Trembling Aspen Forest	Ontario	air temperature, soil temperature, and shortwave irradiance	40
Coxson	2007	Influence of High-Contrast and Low-Contrast Forest Edges on Growth Rates of *Lobaria pulmonaria* in the Inland Rainforest, British Columbia	British Columbia	Edge effects, Canopy cyanolichens, Variable-retention harvesting, growth rates of *L. pulmonaria*	41
Krannabetter	2013	Effectiveness of Green-Tree Retention in the Conservation of Ectomycorrhizal Fungi	Vancouver Island	Canopy cover, species composition, solar radiation, soil temperature, soil moisture	42
Voicu	2006	Microclimatic and Spruce Growth Gradients Adjacent to Young Aspen Stands	Alberta	air temperature, light, soil temperature	42

2.3 Summary of international studies

Table 3 lists 46 selected studies that took place in other countries, listed in alphabetical order by the last name of the study's first author. Annotations for these references are in Chapter 5. Hyperlinked page numbers and lists of study variables are also given in Table 3 for easy referral to each study from this summary.

Table 3. Summary of selected international studies.

First Author	Year	Title	Location	Variables	Page for Annot.
Barik	1992	Microenvironmental Variability and Species Diversity in Treefall Gaps in a Sub-Tropical Broadleaved Forest	India	soil moisture, soil temperature, air temperature, relative humidity, species composition, stem density, photon flux density	43
Bennett	2010	Edge Microclimate of Temperate Woodlands as Affected by Adjoining Land Use	Australia	type of adjoining land use, distance from edge, canopy openness, stem density, basal area, air temperature, VPD	43

First Author	Year	Title	Location	Variables	Page for Annot.
Camargo	1995	Complex Edge Effects on Soil Moisture and Microclimate in Central Amazonian Forest	Brazil	soil moisture volume fraction, rainfall, soil water potential, soil texture, slope, air vapor pressure deficit, and vegetation	44
Cao	2009	Edge Effects on Soil Seed Banks and Understory Vegetation in Subtropical and Tropical Forests in Yunnan, SW China	China	Sunlight, PPFD, air temperature, soil moisture, soil temperature, carbohydrate storage, water storage, pigment composition, Leaf anatomy, leaf physiology, rubisco, tree age	45
Closa	2010	Microclimatic Conditions Determined by Stem Density Influence Leaf Anatomy and Leaf Physiology of Beech (*Fagus sylvatica l.*) Growing within Stands that Naturally Regenerate from Clear-Cutting	Spain	Sunlight, PPFD, air temperature, soil moisture, soil temperature, carbohydrate storage, water storage, pigment composition, Leaf anatomy, leaf physiology, rubisco, tree age	46
Davies-Colley	2000	Microclimate Gradients Across a Forest Edge	New Zealand	soil temperature, air temperature, vapor pressure deficit, wind speed, photosynthetically available radiation	46
Delagado	2007	Edge Effects of Roads on Temperature, Light, Canopy Cover, and Canopy Height in Laurel and Pine Forests	Canary Islands	soil and air temperature, light, canopy cover and height	47
Denyer	2006	Buffering of Native Forest Edge Microclimate by Adjoining Tree Plantations	New Zealand	air temperature, vapor pressure deficit, photosynthetically available radiation	48
Didham	1999	Edge Structure Determines the Magnitude of Changes in Microclimate and Vegetation Structure in Tropical Forest Fragments	Brazil	canopy height, canopy density, air temperature, evaporative drying rate, litter moisture content, litter depth, litter biomass	49
Erdos	2013	Species Composition and Diversity of Natural Forest Edges: Edge Responses and Local Edge Species	n/a*	solar radiation, soil moisture, species composition, species diversity	49

First Author	Year	Title	Location	Variables	Page for Annot.
Fetcher	1985	Vegetation Effects on Microclimate in Lowland Tropical Forest in Costa Rica	Costa Rica	temperature, vapor pressure deficit	50
Fox	1997	Vegetation Changes across Edges of Rainforest Remnants	Australia	species richness, edge disturbance	50
Ghuman	1987	Effects of Partial Clearing on Microclimate in a Humid Tropical Forest	Nigeria	measurements of rainfall, throughfall, relative humidity, solar radiation, evaporation, and air and soil temperatures	51
Gimmi	2010	Land Use and Climate Change in Forest Trajectories in a Dry Central-Alpine Valley	Central Alpines	air temperature, canopy cover, surface disturbance, land use changes	51
Gustafsson	2012	Forestry to Maintain Multifunctional Forests: A World Perspective	n/a	nutrient dynamics, carbon cycling, air temperature, substrate quality, vertical patches	52
He	2012	Effects of Forest Gaps on Microclimate Variables in *Castanopsis kawakamii* Natural Forest	China	air temperature, soil temperature, relative humidity, soil water content, canopy cover, gap area: perimeter ratio	52
Hennenberg	2007	Detection of Season Variability in Microclimatic Borders and Ecotones between Forest and Savanna	Ivory Coast	air temperature, air humidity, and vapor pressure deficit	53
Herbst	2007	Edge Effects and Forest Water Use: A Field Study in a Mixed Deciduous Woodland	England	rain shadow, seasonal water loss, predicted water use per unit ground area	54
Jose	1996	Vegetation Responses along Edge-to-Interior Gradients in a High Altitude Tropical Forest in Peninsular India	India	soil pH, organic carbon, total nitrogen, available phosphorus, soil moisture, light transmittance, relative humidity, and air and soil temperatures	54
Kapos	1989	Effects of Isolation on the Water Status of Forest Patches in the Brazilian Amazon	Brazil	air temperature, vapor pressure deficit, photosynthetically active radiation, soil moisture, and leaf relative water contents	55

First Author	Year	Title	Location	Variables	Page for Annot.
Kapos	1997	Edge-Related Changes in Environment and Plant Responses Due to Forest Fragmentation in Central Amazonia	Brazil	temperature, vapor pressure deficit, soil moisture	56
Korner	2007	Tree Species Diversity Affects Canopy Leaf Temperatures in a Mature Temperate Forest	Switzerland	leaf temperature, canopy density, tree species, branching habits, leaf area density, leaf traits. air temperature	56
Laurance	1997	Hyper-Disturbed Parks: Edge Effects and the Ecology of Isolated Rainforest Reserves in Tropical Australia	Australia	canopy cover, subcanopy cover, amount of woody debris on the ground, abundances of climbing rattans and lianas, number and size of treefalls, and distance of plot to nearest larger forest area edge	57
Laurance	2002	Hyperdynamism in Fragmented Habitats	n/a	edge effects, hyperdynamism, time since fragmentation, abiotic fluxes	58
Lohmus	2010	Epiphyte Communities on Trunks of Retention Trees Stabilize in 5 Years After Timber Harvesting, but Remain Threatened Due to Tree Loss	Estonia	solar radiation, epiphyte diversity and abundance, canopy cover, retention tree numbers, air temperature	58
Lovejoy	1986	Edge and Other Effects of Isolation on Amazon Forest Fragments	Brazil	microclimate variables, edge effects on animals, and plant mortality	59
MacDougall	1992	The Understory Light Regime and Patterns of Tree Seedlings in Tropical Riparian Forest Patches	Belize	light penetration, seedling growth and persistence, distance from fragment edge	59
Morecraft	1998	Air and Soil Microclimates of Deciduous Woodland Compared to an Open Site	England	wind speed, photosynthetically available radiation, vapor pressure deficit, temperature at different heights above ground and into the soil	60
Murcia	1995	Edge Effects in Fragmented Forests: Implications for Conservation	n/a	air temperature, air moisture, VPD, soil moisture, and light	61

First Author	Year	Title	Location	Variables	Page for Annot.
Navarro	2013	The Weight of the Past: Land Use Legacies and Recolonization of Pine Plantations by Oaks	Spain	solar radiation, species composition and richness, stem density, canopy cover, soil temperature, propagule density	61
Newmark	2001	Tanzanian Forest Edge Microclimatic Gradients: Dynamic Patterns	Tanzania	air temperature, vapor pressure deficit, and light intensity	62
Newmark	2005	Diel Variation in the Difference in Air Temperature between the Forest Edge and Interior in the Usambra Mountains, Tanzania	Tanzania	air temperature	62
Pastur	2012	Landscape and Microenvironmental Conditions Influence over Regeneration Dynamics in Old-Growth *Nothofagus betuloides* Southern Patagonian Forests	Patagonia	soil moisture, incident radiation, species composition, canopy cover, soil temperature	63
Pohlman	2007	Edge Effects of Linear Canopy Openings on Tropical Rain Forest Understory Microclimate	Australia	photosynthetically available radiation, air temperature, relative humidity, air speed, canopy temperature, ground surface temperature, soil temperature, and soil moisture	63
Pohlman	2009	Temporal Variation in Microclimatic Edge Effects Near Power Lines, Highways and Streams in Australian Tropical Rainforest	Australia	air temperature, vapor pressure deficit, and wind speed	64
Ribeiro	2009	Tree Structure and Richness in an Atlantic Forest Fragment: Distance From Anthropogenic and Natural Edges	Brazil	type of edge, basal area, diameter, richness, height of first tree branch	65
Ritter	2005	Light, Temperature, and Soil Moisture Regimes Following Gap Formation in a Semi-Natural Beech-Dominated Forest in Denmark	Denmark	photosynthetically available radiation, soil and air temperature, and soil water content	65
Saunders	1991	Biological Consequences of Ecosystem Fragmentation: A Review	n/a	radiation flux, water flux, and wind	66

First Author	Year	Title	Location	Variables	Page for Annot.
Spellerberg	1998	Ecological Effects of Roads and Traffic: A Literature Review	New Zealand-based	meta-analysis, roads impacts on forest environment, fragmentation	67
Turton	1997	Edge and Aspect Effects on the Microclimate of a Small Tropical Forest Remnant on the Atherton Tableland, Northeastern Australia	Australia	soil temperature at three depths, ambient temperature at two levels, and vapor pressure deficit at two levels	68
Von Arx	2013	Microclimate in Forests with Varying Leaf Area Indices and Soil Moisture: Potential Implications for Seedling Establishment in a Changing Climate	Switzerland	vapor pressure gradients, soil moisture, canopy cover, air and soil temperature, stem density, leaf area index	69
Wilcove	1986	Habitat Fragmentation in the Temperate Zone	England	size of fragment, proximity to other fragments, fragment shape, loss of habitat heterogeneity, effects of fragmentation on animals	69
Williams-Linera	1990a	Origin and Early Development of Forest Edge Vegetation in Panama	Panama	soil moisture, canopy openness, seed germination, seed recruitment	70
Williams-Linera	1990b	Vegetation Structure and Environmental Conditions of Forest Edges in Panama	Panama	temperature, humidity, vegetation, tree mortality	70
Young	1994	Microclimate and Vegetation Edge Effects in a Fragmented Podocarp-Broadleaf Forest in New Zealand	New Zealand	air temperature, vapor pressure deficit, and photosynthetically available radiation	71
Zulkiflee	2010	The Effects of Gap Size on Some Microclimate Variables During Late Summer and Autumn in a Temperate Broadleaved Deciduous Forest	England	solar radiation, air temperature, soil temperature, relative humidity, wind speed, soil water content	72

n/a = location site unknown or non-specific

3 Annotation of Selected U.S. Studies

Allen Jr., L. H. 1968. "Turbulence and Wind Speed Spectra within a Japanese Larch Plantation." *Journal of Applied Meteorology* 7(1):73–78. doi: 10.1175/1520-0450(1968)0072.0.CO;2.

This study measured turbulence within and above a plantation of Japanese larch near Ithaca, New York. The larch were spaced about 3 m apart and had a mean height of 1,040 cm. Wind data was taken in October 1964 after partial needle fall and again in November 1964 after total needle fall. The turbulence within the vegetation showed deeper penetration of gusts after needle fall and during high winds. Wind flow data was measured with a sensor system which consisted of cup anemometers and heated-thermocouple anemometers. Aspirated thermopiles were used to measure temperature profiles above the vegetation. The wind data were taken at heights ranging from 115 to 1,569 cm. The study concluded that there is a substantial increase in turbulence at the 725-cm height compared with lower heights.

- *Variables*: turbulence, tree height, needle fall, wind flow

Brown, R. A., G.E. McVehil, R.L. Peace Jr., and R.W. Coakley. 1969. *Characterization of Forest Vegetation Analogs*. Cornell Aeron Lab Tech Rep VT-2408-P-1. 1–98.

This study examines four methods of characterizing forest canopy roughness and discriminating between canopies of different roughness. Actual forest canopy data was not collected; instead, curves were calculated to predict data of forest canopy tests. The study's two purposes were: (1) to characterize forest influences and (2) to develop a forest classification system based on diffusion effects that can be used to discriminate between forests with different diffusion properties. The study concluded that the most important diffusion property is the vertical transfer rate, and that the associated forest properties are the roughness, closure, and density of the canopy.

- *Variables*: roughness, diffusion, vertical transfer rate, closure, canopy density

Cadenasso, M.L., M.M. Traynor, and S.T.A. Picknett. 1997. "Functional Location of Forest Edges: Gradients of Multiple Physical Factors." *Canadian Journal of Forest Research* 27(5): 778–782. doi: 10.1139/cjfr-27-5-774.

The two study sites were in Dutchess County in eastern New York. The sites are 2 km away from each other and are northeastern deciduous forests. Each site totals more than 40 ha and is more than 60 yr old. Sites are considered to be well developed but are still intact. Dominant species include *Quercus rubra, Quercus prima, Betula lenta, Fagus grandifolia, Acer rubrum*, and *Acer saccharum*. The understory consists of *Ostrya virginiana, Hamamelis virginiana, Amelanchier canadensis,* and *Viburnum acerifolium*. The area next to the forest patches consists of successional fields dominated by *Solidago, Poa,* and *Schizachyrium scoparium* species. This article argues that there are many faults with current research on gradients and edge effects, mainly that the gradients between the two habitat types are not often measured but implied. Goals of the study were to identify any correlation between vegetation features and the gradients measured, and to identify all the areas of the gradients by measuring all physical factors from the interior into the nonforested area. The main hypothesis is that "environmental changes associated with the boundary of temperate deciduous forest and field constitutes a multidimensional zone that extends into both community types." Data included: width of edge zones, mean values of photosynthetically available radiation (PAR) relative to distance from edge, mean air temperature values relative to edge, mean soil temperature values relative to edge, and mean values of volumetric soil moisture relative to edge. Findings included: decreased solar noon and maximum air temperatures and soil temperatures further into the forest, increased humidity further into the forest, interior conditions persist beyond the forest edge (as hypothesized), and that differences between the two sites appear to be related to aspect and exposure.

- *Variables*: maximum, minimum, and solar noon air temperatures, relative humidity, photosynthetically available radiation, soil temperature, soil moisture, soil depth

Canham, C.D., J.S. Denslow, W.J. Platt, J.R. Runkle, T.A. Spies, and P.S. White. 1990. "Light Regimes beneath Closed Canopies and Tree-Fall Gaps in Temperate and Tropical Forests." ***Canadian Journal of Forest Research*** **20(5): 620–631. doi: 10.1139/x90-084.**

The five study sites were in: (1) the Cascade Mountains, (2) Ohio, (3) The Great Smoky Mountains, (4) the southeastern United States, and (5) a tropical rain forest in the lowlands of Costa Rica. The Cascade Mountains site is dominated by *Pseudotsuga menziesii*; the Ohio site is dominated by *Fagus grandifolia* and *Acer saccharum*; the Great Smoky Mountain site is dominated by *Magnolia grandifolia*, and the tropical site is dominated by *Pentaclethra macroloba*, and the southeastern site was mixed southern hardwoods. The objective of this study was to gather the data from five different understory light regimes and "examine spatial and temporal variation in understory light levels in response to canopy structure, gap geometry, topography, and latitude." Relevant data for each site included: basic characteristics, mean PAR characteristics, and frequency distributions of potential sunfleck duration beneath closed canopies. Results indicate that even small, single-tree gaps can have a significant effect on understory PAR. The only light regime where this was not true was in the Douglas-fir and hemlock sites attributed to the high ratio of tree height to crown width. Additionally, as a result of site variation, "understory locations may receive similar total photosynthetic photon flux density over a growing season, but with very different temporal patterns of light availability."

- *Variables*: photosynthetically available radiation, photosynthetic photon flux density, canopy gaps.

Chen, Jiquan, Jerry F. Franklin, and Thomas A. Spies. 1993a. "An Empirical Model for Predicting Diurnal Air-Temperature Gradients from Edge into Old-Growth Douglas-Fir Forest." ***Ecological Modelling*** **67(2-4): 179–198. doi: 10.1016/0304-3800(93)90004-C.**

Old-growth Douglas fir forests in southern Washington and central Oregon were studied. The edge of the forest was created via clearcutting 10–15 yr ago, and the forest patches were at least 500 m in diameter. The clearcut area was replanted with conifer species, and the dominant species in the forest patches were Douglas fir, western hemlock, Pacific silver fir, Pacific yew, and western redcedar. Diurnal air temperature gradients were measured along 16 gradients from the edge to the interior of the forest,

and the effect of growing season, edge orientation, and macroclimate were also studied. The gradient was expressed in terms of air temperature in the interior forest, difference in air temperature between the edge and inside the forest, and the changing ratio of temperature along the gradient. The results were that air temperature varied sinusoidally over the simulation period, increasing during the day and decreasing at night with distance from the edge. The temperatures were comparably the same at the edge and in the interior of the forest at mid-morning and late afternoon. South- and west-facing edges had higher gradients than north- and east-facing edges.

- *Variables*: air temperature: maximum, minimum, and average

Chen, Jiquan, Jerry F. Franklin, and Thomas A. Spies. 1993b. "Contrasting Microclimates Among Clearcut, Edge, and Interior of Old-Growth Douglas-Fir Forest." *Agricultural and Forest Meteorology* 63(3-4): 219–237. doi: 10.1016/0168-1923(93)90061-L.

Old-growth Douglas fir forests in southern Washington and central Oregon were studied. The edge of the forest was created via clearcut 10–15 yr ago, and the forest patches were at least 500 m in diameter. The clearcut area was replanted with conifer species, and the dominant species in the forest patches were Douglas fir, western hemlock, Pacific silver fir, Pacific yew, and western redcedar. Data included: the relationships of daily averages and differences in the topics of study in the clearcut, edge, and interior forest, and explanation and documentation of patterns among the three locations. The orientation of the edge was also a factor that was studied, especially its effect on diurnal changes. There were several trends noticed among the three sites, but overall the bottom line was: "generally, a clearcut receives more direct solar radiation and precipitation, loses more outgoing long-wave radiation, and shows higher rates of evapotranspiration than an adjacent forested area...the daily maximums, minimums, and variations were greater during clear than cloudy weather conditions." The trends and the reasoning behind these observations were also explained.

- *Variables*: air temperature, air moisture, soil temperature, soil moisture, short-wave radiation, wind velocity as a function of edge effects

Chen, Jiquan, Jerry F. Franklin, and Thomas A. Spies. 1995. "Growing-Season Microclimatic Gradients from Clearcut Edges into Old-Growth Douglas-Fir Forests." ***Ecological Applications*** **5(1): 74–86. doi: 10.2307/1942053.**

Old-growth Douglas fir forests in southern Washington and central Oregon were studied. The edge of the forest was created via clearcuting 10-15 yr ago, and the forest patches were at least 500 m in diameter. The clearcut area was replanted with conifer species, and the dominant species in the forest patches were Douglas fir, western hemlock, Pacific silver fir, Pacific yew, and western redcedar. The study report contains numerous data and graphs; each variable is analyzed separately but also in relation to significance of edge influence (SEI) and depth of edge influence (DEI). The article came to several conclusions about the patterns noticed for a fragment and a microclimate gradient, and edge orientation was also pointed out as an important factor that would affect a microclimate. "SEI and DEI were found to be necessary measurements for evaluating edge effects on microclimatic variables, which responded differently depending on time of day, edge orientation, and local weather."

- *Variables*: air temperature, soil temperature, relative humidity, shortwave radiation, wind speed, significance of edge influence, and depth of edge influence

Donato, Daniel C., John L. Campbell, and Jerry F. Franklin. 2012. "Multiple Successional Pathways and Precocity in Forest Development: Can Some Forests Be Born Complex?" ***Journal of Vegetation Science*** **23(3):576–84. doi: 10.1111/j.1654-1103.2011.01362.x.**

Some forests exhibit protracted tree establishment with interspecific competition that precludes canopy closure during development and succession. These conditions create prolonged gap and edge effects which can facilitate or exclude shade-tolerant species and maintain species diversity. Clumped, widely spaced trees, vertically heterogeneous crowns and canopies, and co-existence of under-, mid-, and overstories are common characteristics.

- *Variables*: Canopy cover, species diversity, gap and edge measures, species composition, solar radiation, light intensity

Dovciak, Martin, Charles B. Halpern, Shelly A. Evans, and Troy D. Heithecker. 2010. "Forest Management Changes Microclimate and Bryophyte Communities in the Cascade Mountains of Western Washington." COS 109-6. In Ecological Society of America Annual Meetings Abstracts *COS 109, Biodiversity: Effects of Global Change*, 95th ESA meeting held August 1–6.

Overstory trees moderate understory microclimate through direct and indirect shading. Decreasing canopy cover resulted in increased solar radiation and air temperatures which caused significant reductions in bryophyte (mosses and liverworts) abundance, cover, and species richness. These effects will likely be exacerbated by climate warming.

- *Variables*: air temperature, solar radiation, bryophyte diversity and abundance, and substrate quality

Els, Paul van, Karen R. Hickman, Michael W. Palmer, and Rodney E. Will. 2010. "Changes in Forest Understory Associated with *Juniperus* Encroachment in Oklahoma, USA." *Applied Vegetation Science* 13(3): 356–68. doi: 10.1111/j.1654-109X.2010.01078.x.

This study was conducted at Cross Timbers Forest in Payne County, Oklahoma. The sites were dominated by *Q. stellata, Q. marilandica* and *Sideroxylon lanuginosum Michx*. All sites were characterized by a variable *J. virginiana* component in the midstory. Additional common tree species included *Quercus muehlenbergii Engelm., Celtis occidentalis L., Celtis laevigata Willd*, and *Ulmus americana L*. The objective of the study was to determine whether understory vegetation cover and richness decline along a gradient of increasing *Juniperus virginiana* midstory canopy cover, and if that decline is best correlated with litter accumulation. To determine this, vegetation levels were measured in forest gaps, in forest areas without *J. virginiana*, at the inner and outer edge of *J. virginiana* canopies, and near *J. virginiana* trunks. Vegetation differences were then compared among location to variables of light, litter, soil, and microclimate. Study results showed that species richness and summer vegetation cover declined with proximity to the trunks, and that this decline was, in fact, related to *J. virginiana* litter accumulation.

- *Variables*: *Juniperus virginiana* cover, midstory development; photosynthetic photon flux density (PPFD), vegetation levels, litter, light, proximity to trunks

Euskirchen, Eugénie S., Jiquan C. Chen, and Runcheng Bi. 2001. "Effects of Edges on Plant Communities in a Managed Landscape in Northern Wisconsin." ***Forest Ecology and Management*** **148(1-3): 93–108. doi: 10.1016/S0378-1127(00)00527-2.**

The study sites were in red pink and jack pine plantations in the Chequamegon National Forest in Wisconsin. The plantations were established in the 1930s on areas that originally were pine barrens or northern dry forest communities prior to the 1800s. The red pine plantations were subjected to low-disturbance regimes, with partial cutting every 10–15 yr, with high intensity disturbance events occurring only every 100–150 yr. The jack pine plantations were subjected to higher-intensity disturbance regimes, with 40–70 yr between total clearcuts, and other trees being replanted. The main questions the study sought to answer were: "(1) Is there an effect in terms of understory plant species composition and abundance when crossing from a clearcut to an edge to the forest interior in two different types of pine plantations? (2) What are the differences in the effects of edges on understory composition between the red and jack pine plantations? (3) How well can species diversity and total estimated understory cover be predicted from a combination of variables pertaining to forest structure, topography, and composition?" Data included: frequency, mean percent cover, functional group classifications, and DEI of understory plant species, distribution of understory species found in both stands, and a summary of previously selected studies on understory plant species across edges in northern temperate forests. Major conclusions of the study are that species richness does not differ significantly between the edge and clearcut for either the jack pine or the red pine, and that for the red pine there are significant differences in species richness from the edge to the interior and from the clearcut to the interior, with fewer species in the interior. "Our results suggest that a depth-of-edge influence value of around 30 m should be considered when managing landscapes containing these conifer forest-clearcut edges."

- *Variables*: vegetation gradient, differences in forest types, species richness, vegetation edge to interior gradient

Franklin, Jerry F., and Richard T.T. Forman. 1987. "Creating Landscape Patterns by Forest Cutting: Ecological Consequences and Principles." *Landscape Ecology* 1(1): 5–18.

The study site was in primeval Douglas-fir forests in the Pacific Northwest. The article, however, mainly consists of reviews from already existing literature, and only uses the site as an example of the types of cutting. The article argues that "landscape structural characteristics such as patch size, edge length, and configuration, are altered markedly when management regimes are imposed on primeval landscapes." The greatest criticism of the paper seems to be about the type of cutting that occurs in the Pacific Northwest, where 10–20 ha patches are interspersed with uncut forest areas of at least equal size, but there is increasing evidence that this type of land-clearing system increases some types of catastrophic disturbances. Final arguments include that diversity of biotic life will decrease as these catastrophic disturbances increase, and that microclimate will be further and further disturbed.

- *Variables*: patch size, patch-clearing methods

Fraver, S. 1994. "Vegetation Responses along Edge-to-Interior Gradients in the Mixed Hardwood Forests of the Roanoke River Basin, North Carolina." *Conservation Biology* 8(3): 822–32.

The study sites were in the mixed hardwood forests of the Roanoke River Basin in North Carolina. The edges were created in 1937 or earlier, and the dominant species included: *Quercus alba, Acer rubrum, Fagus grandifolia, Liquidamber styraciflua, Carya sp.*, and *Cornus florida*. The edge is a high-contrast edge, and there was an average 32-34 trees on each of the 23 sites examined. The main objective of the study was to determine the distance of edge effects into the forest interior of agriculturally maintained forest edges; this was accomplished by monitoring the "changes in the cover of selected plant species along the edge-to-interior gradient, changes in plant species richness, saplings densities, and the abundance of exotic plant species along the gradient; and the changes in the overall plant species composition." Data included: changes in the percentage cover of six species along the gradient, changes in the mean species richness, relative cover of exotic species, density of saplings along the gradient, and ordination scores for each site relative to distance from the forest edge. Important conclusions drawn included: (a) "forest edges suffer more from the addition of weedy and exotic plant species than from the reduced

abundance of native forest interior species;" (b) "the variances for species richness, relative cover of exotic species, and the cover of many individual species were higher near the forest edge than in the interior;" and (c) "interpretation of the results indicates that edge effects on forest composition could be detected from 10–30 m inside the forest on north-facing edges and to 50 m on south-facing edges."

- *Variables*: percentage cover of individual species, percentage cover of exotic species, species richness, changes in plant cover along the gradient, changes in plant densities along the gradient, changes in overall plant species composition along the gradient

Gehlhausen, S.M., M.W. Schwartz, C.K. Augspurger. 2000. "Vegetation and Microclimatic Edge Effects in Two Mixed-Mesophytic Forest Fragments." *Plant Ecology* 147(1): 21–35.

This study assessed biotic and abiotic variables to understand the effect of edges and orientation on microclimate in Brownfield and Trelease Woods in Illinois, which are natural, mixed-mesophytic forest patches. The oldest trees are 200–300 yr old, and the dominant species are *Quercus macrocarpa, Quercus rubra,* and *Acer saccharum*. The environmental variables that were measured included: relative humidity, carbon dioxide (CO_2) concentration, air temperature, soil temperature, soil moisture, percent canopy openness, and vegetation. Statistical analyses used SAS and CANOCO, and results indicate that "most microclimatic variables show some degree of change with increasing distance from the forest edge. Variables differ, however, in both the degree to which they change over the gradient and the distance at which they stabilize according to the ANOVA." Data included: mean values for microclimate and vegetation variables as a function of distance from the edge, vegetation graphs, and Sorensen's quantitative and qualitative indices of similarity for the plant species surveyed. "Results indicate that microclimatic variables differ in the degree to and distance over which they show and edge effect. Relative humidity shows the widest edge, while light and soil moisture have the steepest gradients. Aspect influences are evidence by the existence of more pronounced edge effects on the south and west edges, except when these edges are protected by adjacent habitat."

- *Variables*: relative humidity, CO_2 concentration, air temperature, soil temperature, soil moisture, percentage canopy openness

Grady, Kevin C. and Stephan C. Hart. 2006. "Influences of Thinning, Prescribed Burning, and Wildfire on Soil Processes and Properties in Southwestern Ponderosa Pine Forests: A Retrospective Study." *Forest Ecology and Management* 234(1–3): 123–35. doi: 10.1016/j.foreco.2006.06.031.

The study site was in northern Arizona, with the dominant species being southwestern ponderosa pine. Four treatments types were included in the study: unmanaged stands, thinned stands, thinned plus burned stands, and wildfire stands. The objective of the study was to: "elucidate the longer-term changes in ecosystem processes and properties following thinning, prescribed burning, and wildfires in southwestern ponderosa pine forests." Total carbon in the soil did not differ significantly among the treatments; amounts of minerals and rates of ammonification, nitrification, and mineralization varied significantly by treatment; ammonification and mineralization were highest in wildfire stands. The hypothesis that higher rates of microbial activity should lead to higher rates of nitrogen changes was confirmed when higher in situ rates of nitrogen mineralization were found in unmanaged rather than managed stands. "The soil microclimate affects microbial activity and rates of N transformations, with increases in soil temperature and moisture generally leading to increased rates of net N transformations."

- *Variables*: nitrogen, oxygen, mineralization, microclimate's effect on microbial activity

Gray, Andrew N., Thomas A. Spies, and Mark J. Easter. 2002. "Microclimatic and Soil Moisture Responses to Gap Formation in Coastal Douglas-Fir Forests." *Canadian Journal of Forest Research* 32: 332–343. doi: 10.1139/X01-200.

The study site was in the Pacific Northwest, in mature (90–140 yr) and old-growth (up to 500 yr) forests. Dominant species include *P. meziesii, Tsuga heterophylla*, and vine maple. The effect of gap formation on microclimate in mature coniferous forests was assessed with measurements collected over a 6-yr period in four stands. Canopy openness, volumetric soil content, and moisture in organic substrates data were also collected to aid the study. Data included: general characteristics of the stands in the study, PAR quanta relative to gap size, percentage of full openness relative to a within-gap position, soil temperature relative to gap size, soil moisture relative to time of year, mean standardized soil moisture response, and

water content in various organic substrates. Direct radiation was abundant in large gaps, and temperature responses were closely correlated with direct radiation. Soil moisture increased in response to canopy caps, and soil moisture is also variable depending on distance from gap edge and orientation. The study authors concluded that the intense effects that these variables have on microclimate in gaps produces a wide variety of microenvironments across gap treatments.

- *Variables*: solar radiation, soil and air temperature, soil moisture, canopy openness, volumetric soil content, and moisture in organic substrates

Halpern, Charles B., Juraj Halaj, Shelley A. Evans, and Martin Dovciak. 2012. "Level and Pattern of Overstory Retention Interact to Shape Long-Term Responses of Understories to Timber Harvest." *Ecological Applications* 22(8): 2049–64.

Retention harvesting preserves canopy cover and minimizes the negative effects of microclimate changes on understory communities. Incident solar radiation, air temperatures, and vapor pressure gradients were all reduced in forests with retention individuals when compared to more traditional harvest schemes. Authors concluded that less than 15% retention is inadequate to maintain understory diversity due to significantly altered microclimate and edge effects

- *Variables*: retention percentages, solar radiation, understory diversity, ambient temperatures

Halpern, Charles B., and J.A. Lutz. 2013. "Canopy Closure Exerts Weak Controls on Understory Dynamics: A 30-Year Study of Overstory-Understory Interactions." *Ecological Monographs* 83(2):221–37.

Changes in forest canopy and understory structure were significant during the 30–45 yr recovery period following clearcutting and burning. Canopy cover increased 400%, and stem count increased 75%. Mean temperatures and incoming solar radiation decreased linearly. North and south aspects showed different recovery trajectories due to soil moisture and understory response. Species diversity and richness of understory community was variable and related to slope and aspect.

- *Variables*: solar radiation, species diversity, canopy cover, temperature, stem density

Heithecker, Troy D., and Charles B. Halpern. 2007. "Edge-Related Gradients in Microclimate in Forest Aggregates Following Structural Retention Harvests in Western Washington." *Forest Ecology and Management* 248(3): 163–73.

The study encompassed three sites in Douglas-fir forests in the Cascade Range in Washington. Stand age, structure, and species composition varied between the sites. At the first site, the forest was 70–80 yr old with a canopy height of 28-33 m and 830-1,000 stems per hectare. Dominant species include western hemlock and western redcedar. At the second site, the forest was 110–140 yr old with a canopy height of 27-32 m and 590-1,000 stems per hectare. Dominant species include Pacific silver fir and *T. heterophylla*. At the third site, the forest was 140-170 yr old with a canopy height of 49 m and 230–300 stems per hectare. Dominant species include *P. menziesii* and vine maple. This article argues "if residual forest aggregates are to serve as temporary refugia for species sensitive to disturbance or environmental stress, microclimatic conditions must be sufficiently buffered to allow for their persistence." The effect of aspect on the variables and gradient was studied, and results were compared to conditions in adjacent harvest areas and larger tracts of undisturbed forest. Results indicated that on hot summer days, most variables were altered more obviously near or at the forest edge, but this alteration varied depending on distance, topography, and overstory structure. Also, the gradients were driven (partly) by solar radiation and advective heating through wind, so average and maximum temperatures in the aggregate were typically higher at greater depths than the levels of light. Data included: gradients in mean and maximum soil temperature, air temperature, and transmitted light (all as a function of distance from the edge), and variation in predicted heat load and overstory structure among forest aggregates and reference environments (harvest area and undisturbed forest). The article suggests that 1-ha aggregates are sufficient to contain areas that are comparable to those in undisturbed forest and are also suitable to allow for aggregate persistence.

- *Variables*: light, air temperature, soil temperature, and soil moisture

Hibbs, David E. 1982. "Gap Dynamics in a Hemlock-Hardwood Forest." *Canadian Journal of Forest Research* 12: 522–27.

The study site was in a 3-ha forest stand in Harvard Forest, Massachusetts. The canopy dates from heavy cuttings that occurred in 1865 and 1885. The composition of the site is 50% hemlock with red oak, red maple, black birch, white pine, yellow birch, and paper birch. Average canopy height is 18–24 m tall, and aside from single-tree losses to wind and ice, the last disturbance occurred in 1959 when small groups of hemlocks were removed to encourage regeneration. The study's main objective was to "present a case study of several openings within a small area of forest and examine the interaction of opening size, species composition, and growth with opening closure as they affect forest dynamics and composition." Data included: growth of tree seedlings in a 4.2-m radius opening and height growth of regeneration in openings in an 18-m canopy height. Main conclusions of the paper are that: "small forest openings offer only temporary growing space and, as such, may be utilized only by understory woody and herbaceous species. Larger openings provide growing space for trees. These species are successful in these openings, primarily because these larger openings take longer to close by lateral growth of the surrounding canopy and secondarily because the regeneration grows faster in them."

- *Variables*: hemlock, regeneration, canopy gaps

Laurance, William F. and Eric Yensen. 1991. "Predicting the Impacts of Edge Effects in Fragmented Habitats." *Biological Conservation* 55(1): 77–92. doi: 10.1016/0006-3207(91)90006-U.

The aim of the work was to develop a protocol "for assessing the ecological impacts of forest edge effects in fragments of natural habitat surrounded by artificial edges." The article claims the model is useful for investigating reserve design options, for management contexts, and for determining effects of fragment size. The three steps required for the model are "(1) identification of focal taxa of particular conservation or management interest, (2) measurement of an 'edge function' that describes the response of these taxa to induced edges," and (3) use of the model to extrapolate edge function parameters to the situation. The only data required for the model are two edge function parameters and the area and perimeter length of the fragment. With this data, the model can theoretically determine the amount of pristine environment contained within the fragments. The

model was tested and proven correct on a 17.8-ha plot in Adams County, Idaho, which had been clearcut 3 yr earlier. The dominant species were *Pseudotsuga menziesii, Abies grandis, Abies concolor, Pinus ponderosa, Pinus contorta, Picea engelmanii,* and *Larix occidentalis*. The conclusion indicated that “the Core-Area Model is appropriate for comparative landscape studies at the regional and sub-regional level, when fragments have similar types of edges.”

- *Variables*: (necessary for the model) perimeter, area, size, shape index

Lutz, James A., Andrew J. Larson, Mark E. Swanson, and James A. Freund. 2012. “Ecological Importance of Large-Diameter Trees in a Temperate Mixed-Conifer Forest.” *PLOS ONE* 7(5): e36131. doi: 10.1371/journal.pone.0036131.

Large-diameter trees dominate the structure and function of temperate forests. Large individuals account for 1.4% of trees, but 49.4% of the biomass, indicating their importance in dictating gap dynamics and edge effects. Large individuals regulate fire, wind, temperature, solar radiation, pathogens, and insects within mixed forest systems and sustain functions such as carbon storage and maintenance of specialist species habitat.

- *Variables*: canopy cover, biomass, solar radiation, climate variables, species composition, species diversity

Matlack, Glenn R. 1993. “Microenvironment Variation within and among Forest Edge Sites in the Eastern United States.” *Biological Conservation* 66(3): 185–94. doi: 10.1016/0006-3207(93)90004-K.

The study was conducted on 10 edge sites of temperate winter deciduous forest in southeastern Pennsylvania and northern Delaware. The sites were covered in mature old-growth forest, and the dominant species were *Quercus* species, *Carya* species, and *Fagus grandifolia*. The study’s aim is to test the idea that physical gradients depend on the availability of light. The mean canopy tree diameter exceeded 40 cm, and three edge types were chosen: (1) recent, (2) where edges were created 5 yr before the study closed and where there was an intact side canopy from shrubs to tree crowns, and (3) embedded where the edge was next to young successional forest instead of fields. Data included: correlations among microenvironmental variables at each of six recently exposed forest edge sites, widths of the microclimatic edge zone, and microclimate effects at

several different sides of different treatment plots. Results were described as: "At all sites the forest understory was darker, cooler, received less rainfall, and maintained lower vapor pressure deficit than adjacent unforested areas. Extensive correlation was observed among microclimate variables at the six recent edge sites," and at those sites vapor pressure deficit, shrub cover, temperature, and overall light decreased with distance from the edge, while litter moisture and humidity increased. "Light levels depended strongly on edge aspect and edge openness." The major implications of this study included: "with side canopy closure, light-related gradients become non-significant," and "litter moisture is more complex than a simple response to local heating," as seen by the regressions that occurred in closed and embedded sites. This study also suggested that "a side canopy is not climatically equivalent to a top canopy and that edge microclimate continues to evolve after side canopy closure." The article suggests a 50-m buffer strip of successional forest to protect against most of the microenvironmental effects monitored in the study.

- *Variables*: vapor pressure deficit, temperature, litter moisture, direct beam radiation.

Matlack, Glenn R. 1994. "Vegetation Dynamics of the Forest Edge – Trends in Space and Successional Time." *Journal of Ecology* 82 (1): 113–23. doi: 10.2307/2261391.

The study sites were in mixed mesophytic, winter-deciduous hardwood forest in southeastern Pennsylvania and northern Delaware. The dominant species included: *Quercus alba, Q. velutina, Q. coccinea, Q. prinus, Carya* sp., and *Fagus grandifolia*. Fourteen sites were chosen, and the main objective of the study was to "test the effects of aspect and successional stage on plant distributions by a historical experiment using human-generated forest edges in the eastern United States." Distributions of individual herb, shrub, and seedling tree species were described at 14 edge sites and compared to microclimatic and edaphic gradients. Four stands were selected in each of the three classes: recent edges, closed edges, and embedded edges; another category was added later (north-facing edges) and only involved two sample stands. Relevant data included the effect of environmental gradients on plant distributions at forest edges. The study showed that "distributions of edge-oriented species corresponded closely to light-related environmental gradients, that edge zone microclimate is strongly influenced by edge aspect in the eastern deciduous forest," and that edge-oriented pattern is estimated to persist at least 100 yr after the side canopy

closes. On the scale of very large forest disturbances, the article also indicates a general pattern of three stages of vegetation flux: (1) pattern formation, (2) reassortment of physical gradients, and (3) pattern relaxation.

- *Variables*: vegetation flux, microclimate gradients (as they relate to vegetation)

Meyer, Cecelia L., Thomas D. Sisk, and W.Wallace Covington. 2001. "Microclimatic Changes Induced by Ecological Restoration of Ponderosa Pine Forests in Northern Arizona." *Restoration Ecology* 9(4): 443–52. doi: 10.1046/j.1526-100X.2001.94013.x.

The study site was in a ponderosa pine forest in northern Arizona, where for the past 5 yr efforts have been made to thin trees and bring the area back to a high-frequency, low-intensity fire regime. The forest structure includes pines established prior to 1870 and other surrounding pines established in the early twentieth century. Small-diameter trees were thinned in 1998, and the study took place before prescribed burning in the following years. The objectives of this study were to: "(1) quantify and compare microclimatic variables in restored and untreated forest, (2) compare microclimatic conditions at fixed points prior to and following treatments, and (3) quantify microclimatic gradients across edges created by ponderosa pine forest restoration." Data include the effect of restoration treatment on air temperature and vapor pressure deficit and a comparison of pre- and post-treatment light intensity, vapor pressure deficit, and air temperature during morning, midday, and evening. Major conclusions from this paper included: "restoration treatments increased sunlight penetration to the forest floor but did not significantly impact ambient air temperature or vapor pressure deficit. Mean values for air temperature and vapor pressure deficit did not differ significantly between treatments, and both variables were higher at the structural edge and in the treated forest in the early hours. Our results show that microclimatic effects of these restoration treatments are generally modest, but the changes are more prominent at specific locations and during certain times of day."

- *Variables*: light intensity, air temperature, vapor pressure deficit

Morgan, Penelope, Amy Pocewicz, and Kelsey Sherich. 2007. "Canopy Characteristics and Growth Rates of Ponderosa Pine and Douglas-Fir at Long-Established Forest Edges." *Canadian Journal of Forest Research* 37(11): 2096–2105. doi: 10.1139/X07-105.

This study compared the canopy structure and productivity of trees near the forest edge with trees located in the interior of the forest. The research was conducted in western Latah and Benewah counties in northern Idaho, with a focus on low-elevation forests dominated by ponderosa pine or rocky mountain Douglas fir. The results indicated that trees located at forest edges had more leaf area, deeper crowns, higher basal area (BA) growth rates, and more sapwood area at breast height than interior trees. The ponderosa pine had significantly higher BA growth efficiency at forest edges than interiors, but Douglas-fir BA growth efficiency did not differ. Edge effects were significant even after accounting for variation in stand density, which did not differ between the forest edge and interior. Although edge trees had significantly greater canopy depth on their edge-facing than forest-facing side, sapwood area was evenly distributed. There was no evidence found which proved growing conditions at the forest edge were currently subjecting trees to stress, but higher leaf area and deeper crowns could result in lower tolerance to future drought conditions.

- *Variables*: leaf area, crown depth, basal area growth rate, sapwood area, proximity to forest edge

Neill, Andrew R., and Klaus J. Puettmann. 2013. "Managing for Adaptive Capacity: Thinning Improves Food Availability for Wildlife and Insect Pollinators under Climate Change Conditions." *Canadian Journal of Forest Research* 43:428–40. doi: 10.1139/cjfr-2012-0345.

Functional relationships between overstory basal cover and understory species composition reflect food availability for wildlife. Lower overstory canopy cover was associated with higher density of flowering, fleshy-fruited, and/or palatable leaf-producing plants that provide food for wildlife and options for pollinators. Lower-canopy cover resulted in increased species composition by drought, heat, and fire tolerant species.

- *Variables*: Canopy cover, species composition, light penetration, species diversity

O'Neal, Michael A., Lyndsey B. Roth, Brian Hanson, and Daniel J. Leathers. 2010. "A Field-Based Model of the Effects of Landcover Changes on Daytime Summer Temperatures in the Northern Cascades." *Physical Geography* 31:137–55. doi:10.2747/0272-3646.31.2.137.

Reduction of forest canopy cover increases daily high temperatures during the summer. Temperature differences are easily observed in individual forest stands; however, precise quantification is difficult to extrapolate across regional scales due to heterogeneous mixtures of stand densities and heights.

- *Variables*: canopy cover, soil temperature, stem density, surface temperatures

Palik, Brian J., and Peter G. Murphy. 1990. "Disturbance Versus Edge Effects in a Sugar Maple/Beech Forest Fragments." *Forest Ecology and Management* 32: 187-202. doi: 10.1016/0378-1127(90)90170-G.

The study sites were in sugar-maple and beech forest fragments in East Lansing, Michigan. The sites were in an old-growth fragment that only experienced minor disturbances. Fencing and occasional trimming of horizontal limbs maintained boundaries. The objectives of the study were to: "(1) examine structural and compositional variation of woody vegetation along edge-to-interior gradients on the northern and southern aspects of two forest fragments, and (2) contrast edge-to-interior woody vegetation patterns in the two fragments, which differed in cultural history." Results indicated a gradient of increasing importance of tolerant maple and beech and of decreasing importance of shade-tolerant species, from the edge to the interior on the southern aspect. The lack of this gradient on the north side of the fragment indicates a narrower extent of forest edge there. The main conclusion of this paper was that "the development of an edge-to-interior vegetation gradient is dependent on the disturbance history of a particular fragment."

- *Variables*: vegetation gradient, compositional gradient, structural gradient

Powers, Matthew D., Kurt S. Pregitzer, and Brian J. Palik. 2008. "Physiological Performance of Three Pine Species Provide Evidence for Gap Partitioning." *Forest Ecology and Management* 256(12): 2127–35.

The study site was in the Chippewa National Forest in north-central Minnesota, where four natural red pine stands were harvested in 2002 to form 0.3-ha gaps that are surrounded by a forest matrix. The dominant species was red pine, which is shade intolerant and relies on mixed-severity fire regimes to regenerate. The objective of the study was to "examine the physiological performance of pine species that vary in shade and drought tolerances across large (0.3 ha) sivicultural gaps." Relevant data included: light availability and predawn xylem water potentials, light-saturated carbon assimilation rates, transpiration, stomatal conductance to water vapor, water-use efficiency, and mass-based foliar nitrogen content, height, and diameter of seedlings. Conclusions from the study were that "light availability was lowest at southern edge locations," but there was no increase from southern gap positions to northern gap positions. There was no trend found in water-use efficiency, but jack pine showed differences in performance depending on understory treatments.

- *Variables*: light availability, gap partitioning, carbon assimilation, transpiration, water-use efficiency

Rambo, T.R., and M.P. North 2009. "Canopy Microclimate Response to Pattern and Density of Thinning in a Sierra Nevada Forest." *Forest Ecology and Management* 257(2): 435–42. doi:10.1016/j.foreco.2008.09.029

This study sought to discover the effects of live-tree retention on forest canopy microclimate. Research was collected at the Teakettle Experimental Forest located in the Sierra National Forest approximately 80 km east of Fresno, California. The mixed-conifer overstory of the forest consists of red firs, white firs, incense cedar, Jeffrey pine, and sugar pine, although study trees were restricted to white firs in an effort to limit any potential confounding. The forest's understory plants include manzanita, bush chinquapin, and snowberry. While several studies have examined the effects of different thinning patterns and densities on surface microclimate parameters up to 2 m height, this study is unique in that it examined temperature and humidity gradients through the vertical forest profile among an overstory-thin, an understory-thin, an unthinned control, and a riparian environment in a Sierra Nevada mixed-conifer forest. Temperature and

humidity were recorded for a year by 60 data loggers placed in 12 trees at 5, 15, 25, 35, and 45 m above the forest floor. Based on the recordings, the overstory-thin treatment resulted in the greatest maximum temperature and vapor pressure deficit (VPD), followed by the understory-thin treatment, the control, and finally the Riparian microclimate which had significantly lower minimums and means, and greater daily ranges of temperatures and VPDs than the control. Results suggest that thinning canopy cover significantly increases the extremes and variability of understory microclimate compared with thinning from below and no-thin treatments.

- *Variables*: air temperature, humidity, overstory density, understory density, height from forest floor

Raynor, Gilbert S. 1971. "Wind and Temperature Structure in a Coniferous Forest and a Contiguous Field." *Forest Science* 17(3): 351–63.

Wind speed and temperature were measured at various heights in and above a 10.5-m tall pine forest on level terrain at Brookhaven National Laboratory at Upton, Long Island, New York, over the course of 5 yr. This data was compared with wind speed and temperature taken at various heights from a nearby field. This study found that wind speeds in the trunk space are greater than those in the canopy for a distance of about 60 m. Wind speeds taken at points deeper than 60 m into the forest vary little from height to midcanopy. During the day, a temperature inversion was found beneath the canopy, and a negative lapse rate was found above the canopy. During the night, it was typical to find an isothermal layer or a slight lapse below the canopy and an inversion above the canopy.

- *Variables*: wind speed, temperature, tree height, canopy cover

Saunders, Sari C., Jiquan Chen, Thomas D. Drummer, and Thomas R. Crow. 1999. "Modeling Temperature Gradients across Edges over Time in a Managed Landscape." *Forest Ecology and Management* 117(1-3): 17–31. doi: 10.1016/S0378-1127(98)00468-X.

The study site was in Chequamegon National Forest in northern Wisconsin in a 50-yr-old pine stand. Common species included: *Pinus resinosa, Pinus bansiana, Betula papyrifera, Acer rubrum, Populus tremuloides, Populus grandidenta, Quercus rubra,* and *Quercus ellipsoidalis*. It should

also be noted "species composition and structure are highly dynamic due to the frequent management activities conducted at the stand scale." The aim of the study was to better define the area of edge influence (AEI; the transitional region between two community types) as a landscape element and to determine the point of maximum influence on temperature relative to the edge. This was achieved through monitoring temperature behavior across the forest-clearing boundary. Data included: scaled temperature at eight different times of day for 6 days across the edge between a 6-yr and 50-yr pine stand, depth of edge influence for temperatures from the edge into adjacent patches, and final equations chosen to estimate temperature. The results indicate that "the total, thermal transitional zone between a clearing and forest stand can vary in width by as much as 45 m over the course of a day," and that the specific equations used in the article are not likely to be generalized, so each edge should be modeled independently.

- *Variables*: temperature

Singer, Irving A., and Smith, Maynard E. 1953. "Relation of Gustiness to Other Meteorological Parameters." *Journal of Meteorology* 10: 121–26.

This article presents 2 yr of data that was processed to show relationships between wind gustiness and other meteorological parameters. The gustiness classification system used at Brookhaven National Laboratory in Upton, New York is defined by the range and appearance of the horizontal wind-direction trace. The study shows that gustiness is closely related to lapse rate and solar radiation, but its association with Sutton's index of turbulence and wind speed is not as distinct.

- *Variables*: gustiness, lapse rate, solar radiation, turbulence, wind speed

Spies, Thomas A., William J. Ripple, and G.A. Bradshaw. 1994. "Dynamics and Patterns of a Managed Coniferous Forest Landscape in Oregon." *Ecological Applications* 4(3): 555-568. doi: 10.2307/1941957.

The study sites were in the Cascade Range in Oregon, and the dominant species were Western hemlock, Pacific silver fir, Douglas fir, noble fir, and western redcedar. The main objectives of the study were to "(1) evaluate satellite imagery as a tool for monitoring and characterizing landscape change and structure in mountainous landscapes dominated by coniferous forests, (2) characterize rates of change in closed canopy conifer forests for

the 16-yr period between 1972 and 1988, (3) characterize changes in landscape pattern resulting from clear-cutting, and (4) contrast the patterns and dynamics of public and private forest landscapes." Results indicate that the closed canopy forest declined 13.2% in the 16-yr period, and that the decline was roughly linear in both privately owned and federal properties. The amounts of interior forest declined, and the percentage of edge increased as well, with more changes occurring on privately owned lands. "Mean interior patch area declined from 160 to 62 hectares...the percentage of interior forest area in large areas decreased. In 1972, 50% of the total study area was in connected concentrations of interior habitat of at least 1000 ha; by 1988 the total had declined to 26%."

- *Variables*: forest interior, total interior area, edge area

Swanson, Mark E., Jerry F. Franklin, Robert L. Beschta, Charles M. Crisafulli, Dominick A. DellaSala, Richard L. Hutto, David B. Lindenmayer, and Frederick J. Swanson. 2011. "The Forgotten Stage of Forest Succession: Early-Successional Ecosystems on Forest Sites." *Frontiers in Ecology and the Environment* 9:117–25. doi: 10.1890/090157.

Early successional forests that develop after disturbance, where gap and edge effects are common, exhibit significant diversity in species and structure. Successional changes include closing of canopy cover, reduced solar radiation and soil temperatures, reduced nutrient flux, and diminishing species diversity.

- *Variables*: Solar radiation, soil temperature. canopy cover, species diversity, nutrient cycling

Thomas, Christoph K. 2011. "Variability of Sub-Canopy Flow, Temperature, and Horizontal Advection in Moderately Complex Terrain." *Boundary-Layer Meteorology* 139(1): 61–81.

This study examined the space-time structure of the wind and temperature as well as the resulting spatial temperature gradients and horizontal advection of sensible heat in the subcanopy of a forest with a dense overstory in moderately complex terrain. Data were collected from a sensor network consisting of 10 stations and were subjected to orthogonal decomposition using the multi-resolution basis set and stochastic analyses including two-point correlations, dimensional structure functions, and various other bulk

measures for space and time variability. Despite some similarities, fundamental differences were found in the space-time structure of the motions dominating the variability of the subcanopy wind and temperature fields.

- *Variables*: wind structure, temperature, advection, subcanopy

Wales, Bruce A. 1972. "Vegetation Analysis of North and South Edges in a Mature Oak-Hickory Forest." *Ecological Monographs* 42(4): 451–471. doi: 10.2307/1942167.

The study sites were Hutcheson Memorial Forest in New Jersey. The site was subjected to burning before 1711, but it has not been burned since that time, and the eastern part of the site has never been cut or cleared. In 1950 a severe storm damaged portions of the forest. Dominant species included: white oak, black oak, red oak, red hickory, and flowering dogwood. The canopy reaches a maximum height of 29 m, and gaps are filled by red maple and white ash. The objective of the study was "to examine the variation in the plant distributions in a forest center and on its north and south edges and to describe and interpret the vegetational transitions." Data included: a summary of interactions and main effects for density and basal area, density per quadrat in the forest center of stems in the seedling and sapling size classes, and a summary of interactions and main effects for density by species or species group. The main conclusions of the study are that just as microclimate variables are dynamic at different boundaries and different aspects, the vegetational transitions are also dynamic at different boundaries and aspects, and that "the penetration of light into the north side is negligible. The adjective influences of wind and precipitation, most active on the north during the dormant season, have the greatest penetration into the stand."

- *Variables*: vegetation gradients, vegetational transitions, microclimate variables relative to vegetation gradients

Weathers, Kathleen C., Mary L. Cadenasso, and Steward T.A. Pickett. 2001. "Forest Edges as Nutrient and Pollutant Concentrators: Potential Synergisms between Fragmentation, Forest Canopies, and the Atmosphere." *Conservation Biology* 15(6): 1506–14. doi: 10.1046/j.1523-1739.2001.01090.x.

The study site was in the Hudson Valley of New York State, and the dominant species were northern red oak, black birch, American beech, red ma-

ple, and sugar maple. One of the sites was next to an abandoned agricultural field that was occasionally mowed, and the other site was next to a field that was actively producing hay. The sites had north-east aspects and had been maintained for at least 40 yr. The main objective of the study was to test for nutrient enhancement near forest edges by examining the chemistry and total nutrient load of throughfall during the growing seasons of 1995 and 1996. To test for interactions between forest-edge structure and biogeochemical function, the study assessed how fluxes changed after the structure of edge vegetation was manipulated. Lastly, the study compared throughfall in both forest edge and interior zones to rain deposition in an adjacent open field. The major conclusion of the study was that "the facts that [Sulfate ion] concentration was significantly higher in the edge than interior zones and that total [sulfur] deposition was higher in the edge zone during the growing season suggest that our forest edges did indeed trap atmospheric substances more efficiently than did nearby forest interiors, at least during the growing season."

- *Variables*: nutrients, pollution, soil retention

Wicklein, Haley F., Dorothy Christopher, Megan E. Carter, and Brent H. Smith. 2012. "Edge Effects on Saplings and Microclimate in a Small Temperate Deciduous Forest Fragment." *Natural Areas Journal* 32(1): 110–16.

Across a square, 2.25-ha forest fragment surrounded by croplands, edge effects were pronounced with significant impacts on sapling characteristics. North and south edges had higher sapling density and light intensity; however, sapling size was significantly lower than east and west edges. Soil moisture, pH, organic matter, and nutrient concentrations showed no significant trends. Light intensity and duration are the most important factors across edge-interior gradients. Edge effects do not appear to penetrate deeply into the forest interior.

- *Variables:* Soil moisture, soil chemistry, solar radiation, temperature, canopy cover, species composition, species diversity, stem density

Xu, M.,Y. Qi, J. Chen, and B. Song. 2004. "Scale-Dependent Relationships between Landscape Structure and Microclimate." *Plant Ecology* 173(1): 39–57.

The study site was in the Missouri Ozark Forest Ecosystem Project (MOFEP) andconsisted of mainly mature upland oak-hickory and oak-pine forests. Dominant species included: *Quercus alba, Quercus velutina, Quercus stellata, Quercus coccinea, Quercus marilandica, Quercus meuhlendbergii, Pinus echinata, Acer* spp., *Cary* spp., *Cornus* spp., *Sassafras albidum*, and *Nyssa sylvatica*. The aim of the study was to "investigate the relationships between microclimate and landscape structure from a fine scale to a broad scale." Data included: (1) microclimate data measured versus modeled along the transect, (2) the coefficients of determination between microclimate and landscape structure variables at 10 m and 800 m according to the output of models, and (3) the effects of spatial scale on the relationships between slope and microclimate variables. "Elevation and all the microclimate variables were negatively correlated at all the scales except for above ground temperature, which was weakly and positively correlated with elevation." In general, the correlations between elevation and microclimate variables became stronger with the increase of scale. The results of the study seem to indicate that "the relationships between landscape structure and microclimate are scale-dependent and that landscape structure may be less important in affecting microclimate at plot scales, but more important at larger scales." As far as the analysis tools were concerned, "both simple correlation analysis and standardized cross-variogram analysis are effective and consistent with characterizing the scale-dependent relationships between landscape structure and microclimate. However, the standardized cross-variogram had the advantage to examine the relationships at large scales over the correlation analysis because the sample size reduced rapidly in the correlation analysis."

- *Variables*: air temperature, soil temperature, soil surface temperature, diurnal temperature range of the aforementioned variables, gravimetric soil moisture, elevation, slope, canopy coverage

4 Annotation of Selected Canadian Study Reports

Bradley, David, Dawn M. Burke, Ken A. Elliot, and Stephen B. Holmes. 2008. "The Effects of Partial Harvest on the Understory Vegetation of Southern Ontario Woodlands." *Forest Ecology and Management* 255: 2204–12.

This study looked at the effects of partial harvesting on the understory vegetation of southern Ontario woodlands. The study sites included 19 mixed maple forests set in an agriculture-dominated landscape. In order to determine any effects of partial harvesting, woodlots that had been recently harvested were compared to lots that had been uncut for at least 24 yr. Research findings confirmed that the richness, diversity and quality of understory vegetation were significantly different between the two groups. More intensive harvesting resulted in added richness and diversity, but primarily in the form of weedy species. Partial harvesting, however, did not seem to alter vegetation composition. While the single tree selection system will have an effect on understory plants, other factors—including past management, disturbance history, and microclimate features—will help determine the quality of the vegetation communities. This article cautions against the removal of large volumes of trees and canopy cover as this could be harmful to conservative plant species.

- *Variables*: level of harvesting, amount of weedy species, vegetation communities, past management, disturbance history, canopy cover

Carlson, Derek, and Arthur Groot. 1997. "Microclimate of Clear-Cut, Forest Interior, and Small Openings in Trembling Aspen Forest." *Agricultural and Forest Meteorology* 87(4): 313–329. doi: 10.1016/S0168-1923(95)02305-4.

The study sites were clearcuts, strips, circles, and closed canopy patches in a trembling aspen forest in Ontario, Canada. The dominant species were trembling aspen, white spruce, and white birch, and the stand was approximately 40 yr old. The canopy was uniform and averaged 19 m tall. The main objective of the study was to "describe differences in microclimate among these forest openings and to examine implications for white spruce regeneration." The study compared seasonal and diurnal microclimate

patterns among the different sites. Data included: summary of canopy treatment characteristics, seasonal radiation totals, seasonal average temperatures, five-day running average of soil temperature, diurnal radiation regime, air temperature regime, and soil temperature regime. The main conclusions of the paper were that "seasonal irradiance totals increase with the size of the canopy opening, the radiation regime in the strip configurations was greatly affected by seasonal timing and sky conditions, and that diurnal air temperature amplitudes increased with opening size from the forest interior to the clearcut." The clearcut had the highest maximum temperature and amplitude. "This study illustrates the increases in irradiance, soil temperature, and extremes of air temperature that occur as the size of forest canopy openings increases."

- *Variables*: air temperature, soil temperature, and shortwave irradiance

Coxson, Darwyn S., and Susan K. Stevenson. 2007. "Influence of High-Contrast and Low-Contrast Forest Edges on Growth Rates of *Lobaria pulmonaria* in the Inland Rainforest, British Columbia." *Forest Ecology and Management* 253(1-3): 103–111. doi: 10.1016/j.foreco.2007.07.008.

The study's objective was to determine whether growth rates and vitality of *L. pulmonaria* were lower along forest edges than in the forest interior. Lichen growth rates were measured in mature forests adjacent to three clearcut blocks and three variable-retention blocks in the upper Fraser River watershed between Prince George and McBride, British Columbia. Contrary to their hypothesis, growth rates of large *L. pulmonaria thalli* were actually enhanced near forest edges. Growth rates of small *L. pulmonaria thalli* placed on ''soft'' edge transects were also greatest at or near stand edges and on retained trees in harvest blocks. However, in the ''hard'' edge transects growth rates of small *L. pulmonaria thalli* show little or no enhancement near edges. These findings suggest that edge effects near clearcuts (hard edges) may have little impact on previously established large *L. pulmonaria thalli*.

- *Variables*: edge effects, Canopy cyanolichens, variable-retention harvesting, growth rates of *L. pulmonaria*

Krannabetter, J.M., L. de Montigny, and G. Ross. 2013. “Effectiveness of Green-Tree Retention in the Conservation of Ectomycorrhizal Fungi.” *Fungal Ecology* 6(5):430–38. doi: 10.1016/j.funeco.2013.05.001.

Habitat fragmentation and the microclimate effects associated with gap and edge effects may negatively impact the long-term effectiveness of using green-tree retention as refugia for ectomycorrhizal fungi. Patches less than 20 m in diameter were of insufficient size to support mature forest fungi due to changes in edge microclimate.

- *Variables*: canopy cover, species composition, solar radiation, soil temperature, soil moisture

Voicu, Mihai F., and Phillip G. Comeau. 2006. “Microclimatic and Spruce Growth Gradients Adjacent to Young Aspen Stands.” *Forest Ecology and Management* 221(1-3): 13–26.

The study sites were in west-central Alberta, Canada, in three boreal mixed-wood fragments. The main objectives of the study were to “examine the effects of distance and direction from adjacent aspen stands on: (1) light levels (in terms of transmittance); (2) soil moisture; (3) frequency of summer frost events; (4) air temperature; (5) soil temperature.” Also, the study examines how growth of white spruce is related to light levels from the adjacent aspen stand and initial tree size. The results demonstrate that “gradient in microclimate occurs across boundaries between the taller closed canopy aspen stands and open patches of planted white spruce.” Edge orientation influenced light and soil regimes, but did not have any influence on air temperature. “Negative effects of shading by young aspen on spruce growth are restricted to a narrow band adjacent to the aspen patch equal to 0.3 times the actual height of the aspen while reduction in frost occurrence by the aspen diminishes rapidly with distance from the aspen.”

- *Variables*: air temperature, light, soil temperature

5 Annotation of Selected International Study Reports

Barik, S.K., H.N. Pandey, R.S. Tripathi, and P. Rao. 1992. "Microenvironmental Variability and Species Diversity in Treefall Gaps in a Sub-Tropical Broadleaved Forest." *Vegetatio* 103: 31–40.

The study site was in a 150-ha, subtropical, broadleaved forest plot in India. Dominant species include *Quercus griffithii*, *Quercus dealbata*, *Quercus glauca*, and *Shima khasiana*. The main objective of the study was to determine "whether gap disturbance regimes and tree replacement processes are similar to those in tropical and temperate forests or to what extent the tree species in the sub-tropical forests depend on microsite variability for their niche differentiation." The study surveyed microclimate conditions, dominance, diversity, and composition of tree seedlings and other vegetation. Relevant data included: physical features and microsite heterogeneity of the treefall gaps, principal components of microenvironmental factors in 12 of the gaps, and species diversity and stem density in treefall gaps. Results indicated that heavy rain and wind created most of the gaps in the forest, and that photon flux density was significantly higher in gaps. Soil moisture, soil temperature, and air temperature did not vary significantly between gaps and understory, but relative humidity and litter depth were significantly lower in the gap. Seasonal variations were only significant for photon flux density, soil moisture, and relative humidity.

- *Variables*: soil moisture, soil temperature, air temperature, relative humidity, species composition, stem density, photon flux density

Bennett, Laura T., Sabine Kasel, Michael Tausz, and Thomas E. Wright. 2010. "Edge Microclimate of Temperate Woodlands as Affected by Adjoining Land Use." *Agricultural and Forest Meteorology* 150: 1138–1146.

The objective of this study was to determine edge effects on remnant vegetation in cleared agricultural landscapes and changes in those effects with reforestation. Study sites were located in the Dergholm region of Victoria, Australia. Native vegetation is predominantly heathy woodlands containing species typically associated with low fertility soils. *Eucalyptus*

arenacea and *Eucalyptus baxteri* are the dominant overstory trees, a mid-canopy layer is absent, and the understory is a diverse heath layer up to 1 m in height dominated by *Leptospermum myrsinoides*. The relevant data for the study includes the type of adjoining land use, distance from edge, and woodland structural attributes such as canopy openness, stem density, and basal area. According to the data from one site, the shade created by the adjacent plantations significantly decreased temperatures and vapor pressure deficit (VPD) at woodland edges in the winter months. Conversely, during the non-winter months, the lower wind speeds at plantation edges led to an accumulation of heat in the break between the two land uses. Another finding of this study was that the edge influence was much less significant within these study sites than in closed forests. In addition, the interiors of these sites were warmer and drier than their edges, whereas closed forest interiors tend to be cooler and moister than their edges. This unique microclimate gradient was explained both by decreasing wind speeds and by positive relationships of temperature and VPD with basal area and stem density.

- *Variables*: type of adjoining land use, distance from edge, canopy openness, stem density, basal area, air temperature, VPD

Camargo, J.L.C., and V. Kapos. 1995. "Complex Edge Effects on Soil Moisture and Microclimate in Central Amazonian Forest." *Journal of Tropical Ecology* 11(2): 205–21.

Edge effects on soil moisture and air vapor pressure deficit were studied in a four year old forest patch in Brazil. It is a semi-isolated 100 ha terra firma forest, and the tree height was 25–40 m tall. The edge was 4 yr old. Relevant questions addressed in the study included: (1) How had variation in microclimate in relation to the forest edge changed over the 4 yr between this study and a previous one? and (2) Does the variation in microclimate related to a forest edge vary with height above the ground? The variables that were measured included: rainfall and soil moisture, soil water potential, soil texture, slope, microclimate, and vegetation structure. Data included: (a) soil moisture fraction at varying heights on different days, both from the control plot and the pasture plot; (b) gravimetric soil water content relative to distance from the forest edge, both in the edge transects and in the control transects; (c) mean soil moisture volume fraction in relation to distance from the forest edge for the driest and wettest periods of the study year; (d) foliage distribution and density relative to the forest edge; and (e) mean standardized vapor pressure deficit relative

to pasture or edge reference points. The study authors concluded they confirm that forest edges are functionally different from continuous forest in terms of microenvironment and hydrological processes, but that the differences are not the straightforward edge-related gradients originally thought and that they change over time based on the increased environmental heterogeneity

- *Variables*: soil moisture volume fraction, rainfall, soil water potential, soil texture, slope, air vapor pressure deficit, and vegetation

Cao, Min, and Luxiang Lin. 2009. "Edge Effects on Soil Seed Banks and Understory Vegetation in Subtropical and Tropical Forests in Yunnan, SW China." *Forest Ecology and Management* 257: 1344–1352.

The two sites used for this study were the Xujiaba area on the northern crest of the Ailao Mountain in Yunnan, China, and the Bubeng area in Xishuangbanna of Yunnan, China. The Xujiaba area is dominated by mid-mountain, moist, evergreen broad-leaved forests and the Bubeng area is covered in severely fragmented Shorea wantianshuea forests (tropical seasonal rainforests). This study looked at the levels of three ecological groups (non-forest species, secondary-forest species and primary-forest species) in edge-soil seed banks and edge understory vegetation, and explored the relationship between the invasion of non-forest species in edge understory vegetation and the accumulation of their seeds in edge-soil seed banks. In the soil seed banks, all three ecological groups were fairly represented along the edge to the interior gradient. However, among the understory vegetation, the non-forest species mostly stayed within the first several meters of the edge, while the secondary-forest species decreased in abundance with distance from the edge, and the primary-forest species increased in abundance with distance from the edge. The conclusion of the study was that the interior environment of the forest was not suitable for the non-forest species and must therefore be maintained to inhibit its germination.

- *Variables*: sunlight, PPFD, air temperature, soil moisture, soil temperature, carbohydrate storage, water storage, pigment composition, leaf anatomy, leaf physiology, rubisco, tree age

Closa, Ivan, and Juan Jose Irigoyen. 2010. "Microclimatic Conditions Determined by Stem Density Influence Leaf Anatomy and Leaf Physiology of Beech (*Fagus sylvatica l.*) Growing within Stands that Naturally Regenerate from Clear-Cutting." *Trees* 24: 1029–43.

This study compared the physiology of sun and shade beech tree leaves growing in clearcut areas to those of adult trees growing in an unmanaged forest. The beech trees used in the study were found in the beech forests of Oderitz in northwest Navarro, Spain. The objective of the research was to compare the anatomical, physiological, and biochemical parameters of both sun and shade beech leaves that had successfully established within clearcut areas. The study areas exhibited very different tree densities and, consequently, very different microclimates. The data collected was then compared with mature trees from an unmanaged forest. Relevant data included photosynthetic photon flux density (PPFD) incidence on sun leaves, air temperature, soil moisture, and soil temperature within the forests. The results indicate that these variables affected water and carbohydrate storage in all trees. As trees became older, PPFD also influenced pigment composition and rubisco activity in sun leaves. Shade leaves from the oldest trees were the most sensitive to PPFD, air temperature, and soil moisture and temperature inside the forest. Conversely, microclimatic parameters only slightly affected the physiology of shade leaves of the beech in the stand with the highest light attenuation. Air and soil temperatures were the parameters that most affected the photosynthetic pigments and carbohydrate storage in shade leaves of the youngest trees.

- *Variables*: Sunlight, PPFD, air temperature, soil moisture, soil temperature, carbohydrate storage, water storage, pigment composition, Leaf anatomy, leaf physiology, rubisco, tree age

Davies-Colley, R.J., G.W. Payne, and M. van Elswijk. 2000. "Microclimate Gradients across a Forest Edge." *New Zealand Journal of Ecology* 24(2): 111–21.

A native broadleaf rainforest in New Zealand was cleared for farming around 1910. *Tawa* tree species dominate the canopy, and the three main tree types included: *Beilschmiedia tawa, Elaeocarpus dentatus*, and *Weinmannia racemosa*. This experiment characterizes a microclimate in a forest edge vs. the climate in a pasture relative to these five variables: sunlight exposure, wind exposure (magnitude and direction), precipitation, temperature (of air and soil), and moisture content (of air and soil). Data

included profiles and graphs of the variable values relative to distance from the fence line, with each variable represented. The results were that wind exposure in the forest averaged 20% of what it was in the open, and this variance increased with the wind strength. On sunny days, air temperature and the vapor pressure deficit were more variable during the day, and there was a greater contrast between pasture and forest. On cloudy days, this difference was minimized. Soil temperature fluctuated with air temperature, but soil changes always lagged changes in air temperature; with the other results of the study, the authors concluded that microclimate gradients are of greatest significance on sunny and windy days. Wind direction and speed (into vs. out of the forest) also had an effect on the gradients.

- *Variables*: soil temperature, air temperature, vapor pressure deficit, wind speed, photosynthetically available radiation

Delgado, Juan D., Natalia L. Arroyo, José R. Arévalo, José M. Fernandez-Palacios. 2007. "Edge Effects of Roads on Temperature, Light, Canopy Cover, and Canopy Height in Laurel and Pine Forests." *Landscape and Urban Planning* 81(4): 328–40.

Pine and laurel forests in the Canary Islands were studied. The laurel forest was dominated by *Laurus azorica*, *Myrica faya*, and *Erica arborea*, with a canopy 9–10 m in height and 80% cover. The pine forest was dominated by *Myrica faya*, *Erica arborea*, and *Chamaecytisus proliferus*, with a canopy 20–30 m in height and 60% cover. Road edge effects on microclimate and canopy structure are studied, and temperature was analyzed as a consequence of road edge effects at four different layers (soil, litter, air at 5 cm and at 1.3 m above ground). Canopy cover, canopy height, and light intensity were also monitored. The roads were narrow asphalt roads and dust trails. Data included graphs of four temperature layers relative to distance from the road edge in both laurel and pine forests, analysis of variance (ANOVA) tests of the road edge effects on all the studied abiotic variables, graphs of canopy height, canopy cover, and light intensity relative to distance from road edge in both laurel and pine forests, and results from the Helmert contrast for the road edge effect. Results indicated that "overall variation in temperature, light and canopy showed a general stabilizing trend within the first 10 m from road edges in laurel and pine forests," and although the stabilization distance is short, this result provides implications for both native and invasive species.

- *Variables*: soil temperature, air temperature, light, canopy cover, height

Denyer, K., B.Burns, and J. Ogden. 2006. "Buffering of Native Forest Edge Microclimate by Adjoining Tree Plantations." *Australian Ecology* 31: 478–89.

The six study sites were 50 km south of Auckland in New Zealand. The native forest fragments were an average size of 31 ha with a maximum size of 200 ha, but the sites chosen were 6–10 ha. Sites were dominated by *Beilshmiedia tawa* and *Dysoxylum spectabile*. Other species present included *Dacrydium cupressinum* and *Phyllocaldus trichomanoides*. The edges were at least 60 yr old, and the plantations trees planted along the edge were 20 yr old. This study sought to explain whether dense plantations (Monterey pine in this study) buffer native fragments from edge effects. Microclimate variables were compared between fragments adjacent to plantation trees and fragments that were next to grazed pasture. The variables were assessed at edge-interior gradients perpendicular to the forest edge, and at edges adjacent to pine plantations and pasture area. Data included: changes in microclimate variables relative to distance from edge, daily patterns of the three microclimate variables, 5-day microclimate pattern numerical (as opposed to graphical) data, and numerical differences between microclimate variables at both edge types over 5 days. Results indicated that all variables had a mid-afternoon peak and minima at night, that the VPD closely followed the microclimate of temperature, and that both lagged behind photosynthetically available radiation. "Mean PAR values were significantly lower at embedded edges that equivalent positions at abrupt edges." This relationship is also true of mean temperature values. The main conclusion drawn is that "where a mature pine plantation tightly bordered native forest fragments, the mid-afternoon microclimate edge effect was eliminated, indicating that dense plantations can buffer adjacent forest fragments, at least for that time of day." Additionally, the study authors estimated that interior-like conditions can be preserved in a buffered area for up to 20 yr.

- *Variables*: air temperature, VPD, PAR

Didham, R.K., and J.H. Lawton. 1999. "Edge Structure Determines the Magnitude of Changes in Microclimate and Vegetation Structure in Tropical Forest Fragments." *Biotropica* 31(1): 17–30.

The study sites were in central Amazonia in Brazil, in a dry upland *terra firme* forest. Four sites (two open and two closed) were chosen and were 10–12 yr old. All edges faced west and were next to pasture. The aim of the study was to display the differences between open edges that have been burned and closed edges that have had vegetation growth over the initial edge, and the effect that open edges have on microclimate. Data included: microclimate variable values relative to edge distance in both edge types, variation in edge penetration distances for the variables, and graphical representation of the main variable trends relative to distance from edge. The article concluded that "for a given edge type, 100-ha fragments had consistently lower canopy height, higher foliage density, higher temperature, higher evaporative drying rate, lower leaf litter moisture content, and lower litter depth than continuous forest, at all distances from the forest edge." The main conclusion, however, was that "edge penetration distances for most microclimate and vegetation structure variables were as much as two to five times greater at open edges than at closed edges."

- *Variables*: canopy height, canopy density, air temperature, evaporative drying rate, litter moisture content, litter depth, litter biomass, edge type

Erdos, L., R. Galle, L. Kormoczi, and Z. Batori. 2013. "Species Composition and Diversity of Natural Forest Edges: Edge Responses and Local Edge Species." *Community Ecology* 14:48–58.

Edge ecology has focused on man-made edges, and little effort has focused on natural forest edges, edge micrometeorology, and edge species composition and diversity. Natural edges tended to be more xeric with lower soil moisture, higher solar radiation and surface temperatures, greater nutrient pulsing, and higher species diversity than more mesic forest interiors or man-made edges.

- *Variables*: solar radiation, soil moisture, species composition, species diversity

Fetcher, N., S.F. Oberbauer, and B.R. Strain. 1985. "Vegetation Effects on Microclimate in Lowland Tropical Forest in Costa Rica." *International Journal of Biometeorology* 29(2): 145–55.

The five study sites were in Costa Rica, in a tree fall gap and a 0.5 ha clearing. The forest is a premontane wet forest with an average canopy height of 32.5 m. The objective of the study was to "characterize the temperature and humidity regimes of understory, gap, clearing, and canopy environments and to describe the effects of the regrowth of vegetation on microclimate in gaps and clearings." Relevant data included: mean temperature and VPD for understory, gap, clearing, and canopy sites in two different seasons over 2-yr period. The study concluded that temperatures were coolest in the understory and warmest in the clearing, with temperatures in the canopy and gap sites being comparable and intermediate between temperatures in the understory and clearing. Average VPD was higher in the canopy than in the gap, and the understory had the lowest vapor pressure deficits. Also, "revegetation in the disturbed sites resulted in a significant reduction in temperature and vapor pressure deficit at 70 cm. After 7–8 months, temperatures and vapor pressure deficits at 70 cm were essentially the same in the clearing as in the gap."

- *Variables*: temperature, vapor pressure deficit

Fox, Barry J., Jennifer E. Taylor, Marilyn D. Fox, and Carole Williams. 1997. "Vegetation Changes across Edges of Rainforest Remnants." *Biological Conservation* 82(1): 1–13.

The forest sites were 13 forest remnants in New South Wales, Australia. The forest is a rainforest, primarily on private land and surrounded by agriculture. The objective of the study was to observe "how different groups of plants vary in species richness and density across edges, using these plants to define the edge zone, and study how these variations are modified by remnant size, level of disturbance, and topographical position of the remnant edge." Major conclusions of the study are that "remnant with minor disturbance had significantly narrower edges than those with major disturbances," and that "with increased disturbance of the edge zone there were fewer rainforest species, a lower total number of species, and an increased proportion of colonizer individuals." "The vegetation composition in the interior of remnants was distinctly different from that at the edge. Rainforest species were most abundant inside remnants. There was a peak in species richness of colonizing plants at the edge of remnants, and a peak

in species richness of weeds just outside the edge that resulted in elevated total species richness at remnant edges."

- *Variables*: species richness, edge disturbance

Ghuman, B.S. and R. Lal. 1987. "Effects of Partial Clearing on Microclimate in a Humid Tropical Forest." *Agricultural and Forest Meteorology* 40: 17–29. doi: 10.1016/0168-1923(87)90051-7.

The study site was in the humid tropics of Okomu, Nigeria, where 30 ha were bulldozed. The common trees species included: *Ceiba pentandra, Poga oleosa, Antiaris Africana, Anonidium manii, Enantia chlorantha, Musanga cecropioides, Strombosia pustulata, Celtis zenkeri*, and *Diospyros alboflavescens*. The forest is reportedly over a century old, and the mean tree density was 1,217 trees per hectare. The main point of the study was to "investigate the effects of partial clearing on rainfall partitioning, relative humidity, solar radiation, free water evaporation, wind run and air and soil temperatures in a high rain forest." Data included: mean values for air and soil temperatures and rainfall at the site for the past 10 yr; monthly throughfall and rainfall from July to December 2 yr in a row; chemical properties of stem flow, throughfall, and rainfall; diurnal fluctuations in humidity and air and soil temperature; relative humidity and solar radiation in the two types of sites; and wind speed. The study found that more solar radiation was received in a cleared area compared to the interior of the forest: wind speed was significantly faster in the cleared area than in the forest (up to 18 times the speed); evaporation was higher in the cleared area; rate of fall of temperature was higher in the cleared area; and the maximum temperature in the cleared area was typically 10°C higher than in the forest plot.

- *Variables*: measurements of rainfall, throughfall, relative humidity, solar radiation, evaporation, air temperature, soil temperature

Gimmi, Urs, Thomas Wohlgemuth, Andres Rigling, Christian W. Hoffmann, and Matthias Burgi. 2010. "Land Use and Climate Change in Forest Trajectories in a Dry Central-Alpine Valley." *Annals of Forest Science* 67(7): 701.

Increased mortality of Scots pine (*Pinus sylvestris*) and deciduous tree encroachment result from interactions between climate warming and past land uses such as grazing and silviculture.

- *Variables*: air temperature, canopy cover, surface disturbance, land-use changes

Gustafsson, Lena, Susan C. Baker, Jurgen Bauhus, William J. Beese, Angus Brodie, Jan Koiki, David B. Lindenmayer, Asko Lohmus, Guillermo M. Pastur, Christian Messier, Mark Neyland, Brian Palik, Anne Sverdrup-Thygeson, W. Jan A. Volney, Adrian Wayne, and Jerry F. Franklin. 2012. "Forestry to Maintain Multifunctional Forests: A World Perspective." *Bioscience* 62(7):633–45.

The study focused on retention forestry, maintaining the continuity of structural and compositional diversity in conjunction with harvesting approaches, results in smaller changes in canopy microclimate, and declines in community diversity. The study authors concluded that vertical patch structure was retained, thereby minimizing changes to nutrient dynamics and overall ecosystem function.

- *Variables*: nutrient dynamics, carbon cycling, air temperature, substrate quality, vertical patches.

He, Zhongsheng, Jinfu Liu, Caiting Wu, Shiquin Zheng, Wei Hong, Ssongjin Su, and Chengzhen Wu. 2012. "Effects of Forest Gaps on Some Microclimate Variables in *Castanopsis kawakamii* Natural Forest." *Journal of Mountain Science* 9(5):706–14.

This study was conducted in the Fujian province of China, where the altitude is between 180–604 m. Air and soil temperatures vary significantly, both seasonally and under variable canopy cover. Relative humidity and soil water content varied between large and small gap size but not between large and medium or medium and small-size gaps. These results illustrate the importance of seasonality and gap size on relative significance of microclimate variables.

- *Variables*: air temperature, soil temperature, relative humidity, soil water content, canopy cover, gap area-to-perimeter ratio

Hennenberg, Klaus Joseph, Dethart Goetze, Jörge Szarzynski, Bettina Orthmann, B. Reineking, I. Steinke, ST. Porembski. 2007. "Detection of Season Variability in Microclimatic Borders and Ecotones between Forest and Savanna." *Basic and Applied Ecology* 9(3): 275–85. doi: 10.1016/j.baae.2007.02.004.

The study site was in Comoe National Park in Ivory Coast. The humid, semi-deciduous forest was comprised of savanna-type species, gallery forest types, and forest islands. The islands were 0.5–200 ha, and dominant species included: *Celtis* spp., *Triplochiton scleroxlyon, Daniellia oliveri, Detarium microcarpum, Lophira lanceolata, Cossopteryx febrifuga,* and *Terminalia macroptera*. Analysis of the relationship between season and microclimate was the purpose of the study, and measurements were recorded from the dry season to the wet season over five time periods. Depth-of-edge influence values were reported and conclusions drawn from them, and they were similar to observations from temperate and tropical forest boundaries found in literature. Data included: five-day mean of diurnal amplitude of VPD, VPD relative to distance in the forest and time of day in both the dry and rainy seasons, and border and ecotone analysis. The article concludes that all microclimatic patterns differed more sharply between forest and savanna in the west season than during the dry season, and that during the wet season the detected microclimate borders were located further towards the savanna. The article implies that a detailed knowledge of microclimate shifts and species' responses is essential for predicting forest core area dynamics.

- *Variables*: air temperature, air humidity, and vapor pressure deficit

Herbst, Mathias, John M. Roberts, Paul T.W. Rosier, Michelle E. Taylor, and David J. Gowing. 2007. "Edge Effects and Forest Water Use: A Field Study in a Mixed Deciduous Woodland." ***Forest Ecology and Management*** **250(3): 176–86.**

The study site was in Wytham Woods in England, a very old, mixed-deciduous forest covering up to 415 ha. Dominant species include *Fraxinus excelsior* and *Quercus robur, Acer campestre,* and *Crataegus monogyna* contribute to the canopy and understory. The objective of the study is to "give a full account of the variability of the edge effect on transpiration in a mixed deciduous forest over a whole season and to quantify the rain shadow effect on the interception loss near a forest edge, and to estimate the seasonal water loss of different forest zones at varying distances from the edge, in order to relate the size of a woodland to its predicted water use per unit ground area." Data included: BA per species for zones in different areas, and rainfall relative to edge distance and wind direction. Results indicate that sap flux differs relative to amount of edge exposure, with a 16% difference in interior trees and a 56% difference in edge trees. Oak trees, however, did not mirror that pattern. Larger oak trees were found near the edge, a variation that caused more spatial variation in ground flora during drier seasons. The major conclusions drawn from the study were that "the ratio of forest versus grassland evapotranspiration will vary depending on the size of the woodland under consideration, and soil water recharge rates under forest can be expected to decrease with decreasing woodland size."

- *Variables*: rain shadow, seasonal water loss, predicted water use per unit ground area

Jose, Shibu, Andrew R. Gillespie, Suman Jacob George, and B.Mohan Kumar. 1996. "Vegetation Responses along Edge-to-Interior Gradients in a High Altitude Tropical Forest in Peninsular India." ***Forest Ecology and Management*** **87(1–3):51–62.**

The study site was a high-altitude tropical forest in peninsular India along the Western Ghats. The main objective of the study was to determine how soil characteristics vary along the edge-to-interior gradient, how microenvironmental factors vary along the gradient, and how plant regeneration patterns are related to these variables. Data included: variation in soil chemical factors as influenced by distance from the edge, variation in microenvironmental factors as influenced by distance from the edge, cor-

relation matrix of edaphic and microenvironmental factors measured along the gradient, and distribution of all tree and shrub species over 5-cm diameter at breast height along the gradient. Relevant results were that "forest edges were characterized by higher light transmittance, higher air and soil temperatures, and lower relative humidity. Soil variables increased toward the forest interior." The forest interior was also much more fertile than the edges, as indicated by a 53.9% increase in carbon, a 47% increase in nitrogen, and 55% in air moisture in the interior. The study concluded that edge effects would appear to penetrate to a distance of 15—30 m into the forest, and that light transmittance plays a significant role in alteration of microclimate and edaphic variables.

- *Variables*: soil pH, organic carbon, total nitrogen, available phosphorus, soil moisture, light transmittance, relative humidity, and air and soil temperatures

Kapos, V. 1989. "Effects of Isolation on the Water Status of Forest Patches in the Brazilian Amazon." *Journal of Tropical Ecology* 5(2): 173–85.

The study sites were rainforest remnants in Brazil, specifically in the Minimum Critical Size of Ecosystems Project. The goals of the study were to investigate: "(1) the extent to which edge-related changes in the environment penetrate into the forest patches, and their possible role in changing evapotranspiration budgets, and (2) the effect of these changes on the water relations of understory plants as a possible indication of how important water stress might be in the community as a whole." Relevant data includes ambient temperature and VPD values relative to distance from the edge, patterns of variation in PAR relative to distance from the edge, and moisture characteristic curves of composite soil samples relative to the edge. Major conclusions of the study were that VPD is higher at the edge of the remnant (with similar patterns observed regardless of patch size), that air temperature is also higher at the edge of the remnant, that PAR is high at edges but decreases rapidly with increasing distance into the forest, that soil moisture content is lower in the outer 10–20 m, that leaf relative water contents increased with distance from the edge (which follows soil moisture and VPD), and that edge effects extend 40 m into the reserve.

- *Variables*: air temperature, vapor pressure deficit, photosynthetically active radiation, soil moisture, and leaf relative water contents

Kapos, V., E. Wandelli, J.L. Camargo, and G. Ganade. 1997. "Edge-Related Changes in Environment and Plant Responses Due to Forest Fragmentation in Central Amazonia." In. *Tropical Forest Remnants : Ecology and Management of Fragmented Communities* (Laurance and Bierregaard, ed.), 33–44. Chicago: University of Chicago Press.

The study site was in a semi-isolated, 100-ha tropical forest in Manaus, Brazil, where two sides had been cleared for pasture in 1984. The article seeks to assess the "edge-related gradients of environmental factors that affect evapotranspiration in forest fragments and plant responses to them." Data included: the relationship between air VPD and distance from edge, relationship between volumetric soil content and distance from edge, and number of plants per square meter relative to distance from the edge for two species. Relevant results included: VPD was increased to a distance of 60 m into the forest due to edge effects, soil moisture was highly variable depending on distance from the edge, plants near the edge had lower leaf water content in 4–5 yr following edge creation, and that the environmental factors created much more complex patterns than originally suggested.

- *Variables*: temperature, vapor pressure deficit, soil moisture, leaf water content

Korner, Christian, Leuzinger, Sebastian. 2007. "Tree Species Diversity Affects Canopy Leaf Temperatures in a Mature Temperate Forest." *Agricultural and Forest Meteorology* 146: 29–37.

This study recorded canopy leaf temperature distribution within a tall, mixed-deciduous forest in northwest Switzerland by means of a construction crane and a high-resolution thermal camera. The 100-yr-old forest is dominated by *Fagus sylvatica L.* and *Quercus petraea*, with *Carpinus betulus L.*, *Tilia platyphyllos Scop.*, *Acer campestre L.*, and *Prunus avium L.* present as companion species. In addition, the site has a strong natural presence of conifers. Both the conifer trees and the deciduous trees with high transpiration or very low-density canopies possessed mean leaf temperatures close to air temperature. In contrast, broad-leaved deciduous species with dense canopies (*Fagus sylvatica, Carpinus betulus,* and *Tilia platyphyllos*) were 4.5–5 K warmer than air temperature. The study illustrates that mean leaf temperatures in forest trees are not adequately explained by either stomatal conductance or leaf dimensions, but strongly

depend on canopy architecture (leaf area density, branching habits) in combination with leaf traits.

- *Variables*: leaf temperature, canopy density, tree species, branching habits, leaf area density, leaf traits, air temperature

Laurance, William F. 1997. "Hyper-Disturbed Parks: Edge Effects and the Ecology of Isolated Rainforest Reserves in Tropical Australia." In *Tropical Forest Remnants: Ecology and Management of Fragmented Communities* (Laurance and Bierregaard, ed.), 71–83. Chicago: University of Chicago Press.

The study sites were 500 ha plots in tropical Queensland, of which the larger forest area had been fragmented over a century ago. The two sites were primarily complex, mesophyll vine forests and had been isolated from the larger forest area for approximately 80–90 yr at the time of the study. Four main treatment groups were used: continuous forest interiors, continuous forest edges, fragment interiors, and fragment edges. The aim of the study was to compare structural damage relative to changed micro-climate variables between the four treatment groups, and to determine likelihood of similar-sized remnants being jeopardized in the future. Relevant data included: comparison of the physiognomic variables between the four treatment groups using Kruskal-Wallis tests, pairwise comparisons between the four treatments, mean estimates of six variables recorded in all four treatment groups, and predictors of forest damage in random plots. Results indicated that wind turbulence can render smaller fragments hyper-disturbed, but can still have significant effects on larger plots (2,000–4,000 ha), and that "chronic wind disturbance may result in ecological changes in fragments that render them increasingly prone to future disturbance." Also, when forests are fragmented, the increased exposure to wind speed, turbulence, velocity, and altered microclimate variables leads to greater windthrow and greater forest structural damage.

- *Variables*: canopy cover, subcanopy cover, amount of woody debris on the ground, abundances of climbing rattans and lianas, number and size of treefalls, and distance of plot to nearest larger forest area edge

Laurance, William F. 2002. "Hyperdynamism in Fragmented Habitats." *Journal of Vegetation Science* 13(4): 595–602. doi: 10.1111/j.1654-1103.2002.tb02086.x.

The article is a review of previous literature and analyzes edge effects and the resulting hyperdynamism in wooded areas. It defines hyperdynamism as an increase in the frequency and/or amplitude of population, community, and landscape dynamics in fragmented habitats. There are seven potential causes of hyperdynamism in fragmented landscapes: (1) disturbances during initial isolation, (2) changing population dynamics, (3) increasing extinction rates, (4) changes in trophic structure, (5) increasing species turnover, (6) abiotic ecosystem fluxes, and (7) edge effects of the surrounding landscape. These causes and their interactions indicate that a greater emphasis on "understanding the nature, causes, and consequences of dynamic changes in fragmented landscapes." Major questions that the article raises included: Are fragmented systems chronically hyperdynamic? What are the major drivers of that particular hyperdynamism? How do these drivers change over time? Are the dynamics strongly influenced by fragment size? How are animal and plant communities affected and have effects on the dynamics?

- *Variables*: edge effects, hyperdynamism, time since fragmentation, abiotic fluxes

Lohmus, A., and P. Lohmus. 2010. "Epiphyte Communities on Trunks of Retention Trees Stabilize in 5 Years After Timber Harvesting, but Remain Threatened Due to Tree Loss." *Biological Conservation* 143:891–98.

Light stress and increased susceptibility to desiccation for epiphyte communities result from changes in forest microclimate due to harvesting and edge effects. Epiphyte communities change in response to changes in solar radiation, increased air temperatures, and reduced substrate moisture content. Addressing microclimatic stress during retention harvesting operations limits negative impacts on epiphytes.

- *Variables*: solar radiation, epiphyte diversity and abundance, canopy cover, retention tree numbers, air temperature, substrate moisture

Lovejoy, T.E., R.O. Bierregaard Jr., A.B. Rylands, J.R. Malcolm, C.E. Quintela, L.H. Harper, K.S. Brown Jr., A.H. Powell. G.V.N. Powell, H.O.R. Schubart, H.O.R. 1986. "Edge and Other Effects of Isolation on Amazon Forest Fragments." In *Conservation Biology: The Science of Scarcity and Diversity* (M.E. Soulard, ed.), 185–257. Sunderland, MA: Sinauer Associates, Inc.

The study site was in the Minimum Critical Size of Ecosystems Project in Manaus, Brazil. The tropical forest there is being studied as part of a long-term (over 20 yr) study on the effects of fragmentation. Fragments of varying sizes were studied, and the following variables were monitored: microclimate changes, plants, crowding and persistence in understory birds, edge effects on birds, area effects on primates, invasion by second-growth insect species, and varied effects on other animals and invertebrates (most notably ants). Main conclusions drawn from the microclimatic data from the study included: "vegetation within two meters of the edge is visibly affected within days. Increased insolation (particularly early in the morning and late in the afternoon) and hot, dry winds coming off the surrounding clearing alter the physical environment, with consequences for the flora and fauna within the reserve." This particular study provides excellent data on how the trophic structure is affected by edge effects and not just microclimate.

- *Variables*: microclimate variables, edge effects on animals, plant mortality

MacDougall, A. and M. Kellman. 1992. "The Understory Light Regime and Patterns of Tree Seedlings in Tropical Riparian Forest Patches." *Journal of Biogeography* 19(6): 667–75.

The Belize study sites were in a savanna steppe area with an elevation of 500 m. Prominent species in the fragmented riparian forest include *Pinus caribea* and *Pinus oocarpa*. The main site was a 0.85-ha patch with 55 species. The main objective of the study was to "examine the light understory regime of tropical moist forest fragments that exist in the riparian zones of a Central American savanna, to examine the response of forest tree seedlings to variations in light intensity in these forests and to evaluate whether sufficient light variability occurs to permit the co-existence of a variety of light-mediated seedling regeneration strategies." Relevant data included: overall light intensities at three sites in terms of percentage of full light, the estimated distance from the forest edge to the transition

from edge to interior light zones, and light intensities in the edge and interior zones at three sites. Major conclusions drawn by the study are that the penetration of light from the boundary appears to be the most important influence on the distribution of light into the understory, and that canopy gaps and topography variation seem to have little effect. Additionally, the data in the study "suggests that deep edge effects at recently created tropical forest boundaries may gradually be reduced by the development of a more insulative forest boundary."

- *Variables*: light penetration, seedling growth and persistence, distance from fragment edge

Morecroft, M.D., M.E. Taylor, and H.R. Oliver. 1998. "Air and Soil Microclimates of Deciduous Woodland Compared to an Open Site." *Agricultural and Forest Meteorology* 90(1–2): 141–56. doi: 10.1016/S0168-1923(97)00070-1.

The study sites were two 3-yr-old sites in Oxford, England. Measurements were taken from three types of sites including a grassland site, a high forest site, and an abandoned coppice. The site was a temperate, deciduous woodland dominated by *Acer pseudoplatanus* and *Quercus robur*. The study's aim was to calculate mean values for microclimate variables in the forest and coppice during all four seasons and to compare those values to the mean values of microclimate variables in the nearby grassland. Data included: air and soil temperatures for various days in different seasons of the year for all three treatment locations, difference in temperature in woodland air and soil temperatures and grassland air temperatures, mean VPD and vapor pressure in successive seasons at the three sites, wind speeds at the three sites, daily totals of solar radiation measurements throughout the monitoring period, and difference in soil water content at the three sites. Relevant results included: "canopy development and total solar radiation were both significant, and high wind speed had an effect, presumably as a result of the increased mixing of the air," and that "soil temperatures are more affected by the presence of a forest or woodland canopy than air temperatures."

- *Variables*: wind speed, photosynthetically available radiation, vapor pressure deficit, temperature at different heights above ground and into the soil

Murcia, C. 1995. "Edge Effects in Fragmented Forests: Implications for Conservation." *Tree* 10(2):58–62.

This article reviewed many other studies that have taken place in the area of edge effects and microclimate in fragmented forests. The article states that there are three types of edge effects: (1) abiotic effects (e.g., microclimate variables), (2) direct biological effects, and (3) indirect biological effects. To quote from the article's findings: "Diurnal temperatures in pastures and crops tend to be higher near the ground, and daily temperatures fluctuate more widely. The environment under the forest canopy, in contrast, is cooler, moister, and more uniform. Compass orientation determines the amount of exposure to solar radiation." Differences in the values of air temperature, air moisture, VPD, soil moisture, and light vary to almost 50 m into the fragment. The article also indicated that it is unrealistic to expect that all edge effects vary monotonically into the fragment; rather, variables interact with each other in different ways. Referring to the lack of consensus between other edge effect and microclimate studies, the articles asserted that is due to an overly simplistic view of forest edges.

- *Variables*: air temperature, air moisture, VPD, soil moisture, and light

Navarro-Gonzalez, Irene, Antonio J. Perez-Luque, Francisco J. Bonet, and Regino Zamora. 2013. "The Weight of the Past: Land Use Legacies and Recolonization of Pine Plantations by Oak Trees." *Ecological Applications* 23(6):1267–76.

Native forest regeneration is dependent upon in-situ biological legacies. Recolonization was accompanied by decreases in solar radiation and soil temperatures. Understory diversity and species richness increased as did the ratio of oak:pine canopy cover.

- *Variables*: solar radiation, species composition and richness, stem density, canopy cover, soil temperature, propagule density

Newmark, William D. 2001. Tanzanian Forest Edge Microclimatic Gradients: Dynamic Patterns. *Biotropica* 33(1): 2—11.

The four study sites were in the Amani Nature Reserve in northeastern Tanzania. The dominant genera of trees were *Afrosersalisia, Allanblackia, Celtis, Drypetes, Ficus, Isoberlinia, Leptonychia, Macaranga, Myrianthus, Newtonia, Parinari, Sorindeia, Strombosia, Syzygium*, and *Tabernaemontana*. The study aimed to "(1) compare the estimated slopes of forest edge and forest interior gradients, (2) document the relative frequency in the shapes of forest edge and forest interior microclimatic gradients, (3) estimate edge width, and (4) calculate the relative change in microclimate between the forest edge and interior. Measurements were taken on an hourly basis along trails that ran perpendicular to the forest edge. The four study sites had edges between 40– 100 yr old, and the intact forest patches were comparable in terms of vegetation and structure. Data included: summary for the days of observations and number of gradients measured spanning the length of the study, a graph of the relative frequency in the shapes of microclimate gradients along transects, and individual graphs of data for each microclimate gradient variable relative to distance from the edge of the transect. The main conclusion of this article was that the gradients "showed considerable temporal variation in the edge width and relative change in microclimate from forest edge to interior," and that there was low spatial variation for air temperature or vapor pressure deficit.

- *Variables*: air temperature, vapor pressure deficit, and light intensity

Newmark, William D. 2005. "Diel Variation in the Difference in Air Temperature between the Forest Edge and Interior in the Usambra Mountains, Tanzania." *African Journal of Ecology* 43(3):177–80. doi: 10.1111/j.1365-2028.2005.00557.x.

The study site was in a sub-montane forest in Tanzania. The edge of the forest is very abrupt and is bordered by agricultural land or roadways. The aim of the study was to report on the diel variation in air temperature between the edge and the interior, and specific objectives of the study included: (1) examine the difference in air temperature between the edge and interior rather than the shape of the edge microclimate gradients, (2) record air temperature across all sites simultaneously rather than sequentially, and (3) examine temperatures over a 24-hr time frame instead of an 11-hr time frame. The study also sought to answer whether diel differences

vary seasonally and whether diel differences vary by elevation. Results indicated that the differences between air temperature at the edge and in the interior varied relatively continuously throughout the 24-hr period, and that "the difference in air temperatures between the forest edge and interior is much less than the difference in air temperature between sites exterior to the forest and sites interior to the forest edge."

- *Variable*: air temperature, seasonal variation

Pastur, G.M., C. Jordan, R.S. Esteban, M.V. Lencinas, H. Ivancich, and G. Kreps. 2012. "Landscape and Microenvironmental Conditions Influence over Regeneration Dynamics in Old-Growth *Nothofagus betuloides* Southern Patagonian Forests." *Plant Biosystems* 146(1):201–213. doi: 10.1080/11263504.2011.650725.

Old-growth forests contain a mosaic of structural and microclimatic conditions. Forest floor microclimate (temperature, incident radiation, soil moisture, bare ground) determined recruitment, seedling age and distribution patterns, and understory composition.

- *Variables*: soil moisture, incident radiation, species composition, canopy cover, soil temperature

Pohlman, Catherine L., Stephan M. Turton, and Miriam Goosem. 2007. "Edge Effects of Linear Canopy Openings on Tropical Rain Forest Understory Microclimate." *Biotropica* 39(1): 62–71.

The study site was in a complex mesophyll forest in Queensland, Australia. The forest had been disturbed by logging and scattered mining activities prior to 1950. The aim of the study was to investigate the nature of microclimate edge gradients associated with three different types of linear canopy opening: a watercourse, a power line, and a highway. Specific questions included: "(1) Do linear canopy openings produce horizontal microclimatic gradients in the adjacent rainforest understory? (2) Do these edge gradients differ among edge types? (3) How do these edge gradients differ between the wet and the dry season?" Relevant data included: effects of distance from edge, edge type, and season on microclimate variables and variation in microclimatic parameters with distance from the forest edge. The article concluded that the understory was warmer and drier near highway edges in both dry and wet seasons, and that the temperature was elevated in the wet season. Also, effects dissipated 20–25 m away from the

edge at both the power line and the highway sites, but that light was most elevated near the creek, with an edge that extended up to 50 m into the forest. This result implied that "contrasts in edge gradients in air temperature, vapor pressure deficit, and canopy temperature between power line, highway, and creek edges may have been influenced by differences in the nature of the linear canopy openings themselves."

- *Variables*: photosynthetically available radiation, air temperature, relative humidity, air speed, canopy temperature, ground surface temperature, soil temperature, and soil moisture

Pohlman, Catherine L., Stephen M. Turton, and Miriam Goosem. 2009. "Temporal Variation in Microclimatic Edge Effects Near Power Lines, Highways and Streams in Australian Tropical Rainforest." *Agricultural and Forest Meteorology* 149(1): 84–95. doi: 10.1016/j.agrformet.2008.07.003

The study sites were in the Wet Tropics World Heritage Area of northeastern Queensland, Australia, in a complex mesophyll vine forest. Edge disturbance occurred 15 yr prior to the study, and three types of canopy openings were studied: highways, power lines, and streams. Relevant questions addressed by the article included: "are linear canopy openings associated with microclimatic edge gradients in the adjacent rainforest understory as occurs adjacent to larger clearings, do any such edge gradients differ among edge types, and how do edge gradients vary seasonally and diurnally?" Data included: seasonal and diurnal variation in edge gradients of air temperature, VPD, and wind speed and variation in edge extent and direction for the three canopy opening types. The main conclusion was that "maximum wind speeds were elevated near all forest edge types," most notably at stream edges, but that temperature and VPD experienced stronger effects near power lines and highways. The conclusion was that "linear clearings for roads and power lines are associated with microclimatic edge gradients similar to those observed in other studies at forest edges adjacent to larger clearings."

- *Variables*: air temperature, vapor pressure deficit, wind speed

Ribeiro, Maira Taquiguthi, Flavio Nunes Ramos, Flavio Antonio Maës Dos Santos. 2009. "Tree Structure and Richness in an Atlantic Forest Fragment: Distance from Anthropogenic and Natural Edges." ***Viçosa*** **33(6): 1123–32.**

This study area was located in the coastal mountain range of the Serra do Palmital, Saquarema, in the State of Rio de Janeiro, Brazil. It compared the structure and richness of tree communities in three habitats including a man-made edge, a natural edge, and the fragment interior of the Atlantic forest in Rio de Janeiro. The objective of the study was to reveal whether forest fragmentation produces biotic and abiotic differences between edges and the fragment interior. There were 1,076 trees with a diameter at breast height of greater than 4.8 cm, belonging to 132 morphospecies and 39 families that were sampled in a total study area of 0.75 ha. The results showed that the natural edge had the greatest BA, and the trees in this habitat had the greatest diameter; by contrast, the man-made edge had a lower richness and greater variation in the height of the first tree branch. Tree density, diameter, height, and the proportion of standing dead trees did not differ among the habitats. These results indicated that the forest interior and the fragment edges (natural or man-made) do not differ significantly in this studied area.

- *Variables*: type of edge, basal area, diameter, richness, height of first tree branch

Ritter, Eva, Lise Dalsgaard, and Katrina S. Einhorn. 2005. "Light, Temperature, and Soil Moisture Regimes Following Gap Formation in a Semi-Natural Beech-Dominated Forest in Denmark." ***Forest Ecology and Management*** **206(1—3):15–33. doi: 10.1016/j.foreco.2004.08.011.**

The study site was in a semi-natural, beech-dominated forest in Denmark, where common tree species included: *Fagus sylvatica*, *Fraxinus excelsior*, *Quercus robur*, and *Ulmus glabra*. The aim of the study was to "describe temporal and small-scale spatial variation in microclimate and soil moisture levels in and around a small canopy gap." The gap had a diameter of 24 m and was irregularly shaped with an average crown height of 18m. Average canopy height was 31 m, and the gap was created in 1999. "The focus was on gradients along the forest-gap continuum and to suggest causes of these gradients in the first 2–3 years following gap formation." Data included: average PAR, monthly averages of daily maximum soil temperatures, soil water content, mean volumetric soil water content, and

percentage of ground cover of vegetation. Relevant results included: "an increase in the photosynthetically available radiation in the central and northern parts of the gap during the first growing season was observed," and that "generally, our study indicates that differences between gap and forest conditions may already decease within a few years after gap formation."

- *Variables*: photosynthetically available radiation, soil and air temperature, soil water content

Saunders, Denis A., Richard J. Hobbs, and Chris R. Margules. 1991. "Biological Consequences of Ecosystem Fragmentation: A Review." *Conservation Biology* 5(1): 18–32. doi: 10.1111/j.1523-1739.1991.tb00384.x.

This article reviews a wide variety of the studies done on edge effects and microclimate thus far, and includes reasons why edge effects differ and in what categories. Forest remnants differ in that they: are situated on different types of soil, are at different positions in the landscape, have different types of vegetation, have had their edges made for different reasons, and vary in their size, shape, and isolation. The aim of the paper was to "point out the physical effects of fragmentation, the biological consequences for natural ecosystems of these effects, and the options available for conservation research and management." Microclimate changes include changes in radiation flux, wind, and water flux, and these changes are affected by: the time since isolation, the distance from other remnants, the connectivity, and changes in the surrounding landscape, remnant size, remnant shape, and position in landscape. In terms of radiation flux, by altering an environment and creating a fragment, the radiation balance is altered by "increasing the solar radiation reaching the ground surface during the day, changing the albedo, and increasing radiation at night." Additionally, in these newly cleared areas, the daytime temperatures are higher and the nighttime temperatures are lower, which leads to a greater temperature range and a greater incidence of frost. Secondary vegetation will also grow in the cleared area, and can extend from 10–25 m around the edge. Soil will be heated due to increased radiation, which will alter nutrient cycling and possibly affect vertebrate and invertebrate activity based on litter decomposition and soil moisture retention. With wind, direct physical damage will be experienced or humidity will be reduced and desiccation will be increased. Also, dust, debris, and seeds from the surrounding area will be transported further into the forest as a result of increased wind speed.

With water flux, removal of native vegetation and colonization by secondary growth alters the amount of rainfall interception and consequently changes soil moisture levels.

- *Variables*: radiation flux, water flux, and wind

Spellerberg, Ian F. 1998. "Ecological Effects of Roads and Traffic: A Literature Review." *Global Ecology and Biogeography Letters* 7(5): 317–33. doi: 10.2307/2997681.

This study reviewed articles documenting the ecological effects of roads and traffic. The review was done in New Zealand, and the literature was comprised mostly of studies done in the United States, United Kingdom, the Netherlands, Australia, and New Zealand. The studies are from a variety of different forest types and different road and traffic structures. Relevant data included a summary of the ecological effects of roads: effects during construction, short-term effects of a new road and long-term effects, as well as a topical list of studies and articles that deal with road effects. The topics that were considered included: environmental cost of roads, environmental effects of secondary activities, interactions between biota and roads, impacts of traffic and tourism in new areas facilitated by new roads, effects of roads on the physical environment, structures associated with roads, de-icing agents, and geological conservation. Major topics that were more closely studied were pollution and disturbance effects on biota and ecosystems which included: noise and artificial lighting, dust and sand, heavy metals, gases, effects of aquatic systems and biota, habitat fragmentation by roads, edge effects and microclimates in forests, effects on fragmentation on animals and trophic consequences, and the traffic and dispersal of plant species. The main conclusion of the study suggested that more research is needed about fragmentation caused by roads, specifically, because many of the studies that were reviewed had broader points of focus.

- Variables: Meta-analysis, roads impacts on forest environment, fragmentation

Turton, S.M. and H.J. Freiburger. 1997. "Edge and Aspect Effects on the Microclimate of a Small Tropical Forest Remnant on the Atherton Tableland, Northeastern Australia." In *Tropical Forest Remnants : Ecology and Management of Fragmented Communities* (W.F. Laurance and R.O. Bierregaard, ed.), 45–54.Chicago: University of Chicago Press.

The study site was in a 20-ha rainforest remnant in Australia. The forest is a complex mesophyll forest, and selective logging has not occurred for 60–70 yr. The study aimed "(1) to quantify microclimatic gradients along a series of replicated edge-to-interior transects under dry and wet conditions in the summer, (2) to compare the distances to which edge effects penetrate into the remnant among edges with differing aspects, and (3) to determine whether seedling densities vary with distance from the edge and edge aspect." Relevant data included: two way analyses of variance showing effects of distance, aspect, and interaction of distance and aspect and soil surface temperature, ambient temperature, and VPD relative to distance from edge. Canopy cover was relatively high throughout the fragment and negatively correlated with distance from the edge, which was clearly defined. Soil temperatures were affected by distance from the edge and tended to be higher near the edge but stabilized within 30 m. Ambient temperatures and vapor pressure deficit were not clearly affected by distance from edge, but "varied significantly with edge aspect." Under both dry and wet conditions, edge effects were observed up to 30 m, and the authors cited the heavy vegetation that had become established near the edge as the reason behind this relatively small distance.

- *Variables*: soil temperature, ambient temperature, and vapor pressure

Von Arx, G., E.G. Pannatier, A. Thimonier, and M. Rebetez. 2013. "Microclimate in Forests with Varying Leaf Area Indices and Soil Moisture: Potential Implications for Seedling Establishment in a Changing Climate." *Journal of Ecology* 101(5):1201–13. doi: 10.1111/1365-2745.12121.

Forest microclimate is crucial for growth and survival of seedlings. Micrometeorological data from open and dense canopy coverage were measured within 11 forest ecosystems. Data strongly suggest a threshold canopy coverage which is linked to water availability. Open canopy exhibited drier soils, higher temperatures, higher vapor pressure gradients, and higher leaf area indices.

- *Variables*: vapor pressure gradients, soil moisture, canopy cover, air and soil temperature, stem density, leaf area index

Wilcove, D.S., C.H. McLellan, and A.P. Dobson. 1986. "Habitat Fragmentation in the Temperate Zone." In *Conservation Biology: The Science of Scarcity and Diversity* (M.E.Soule, ed.), 237–56. Sunderland, MA: Sinauer Associates, Inc.

The study site was in Dorset, England, in heathland that had been severely fragmented into over 450 pieces. The aim of the study was to determine: "(1) What is the effect of fragmentation on the species originally present in the intact habitat? (2) How does fragmentation lead to the loss of species? 3) For an already fragmented landscape, are there any guidelines for the selection and management of nature reserves?" Data included: incidence functions for two species in the fragments and the number of species remaining as fragmentation proceeds. The author indicated that although vegetational changes and edge effects may only extend 10–30 m into the forest (depending on aspect), interactions between the flora and fauna in response to these changes are what drives extinction or the disappearance of a species in that area.

- *Variables*: size of fragment, proximity to other fragments, fragment shape, loss of habitat heterogeneity, effects of fragmentation on animals

Williams-Linera, G. 1990a. "Origin and Early Development of Forest Edge Vegetation in Panama." *Biotropica* 22(3): 235–41.

The study site was in the Tropical Premontane Wet Forest life zone in Panama, where the edge was parallel to the slope on a small hill crest. The two species that were studied were *Paulownia tomentosa* and *Phytolacca rivinoides*. The objectives of the study were to: "investigate why light-demanding species are rare on forest edges; to determine whether the source of edge plants is the seed bank or the seedlings and saplings present before the edge was created; and to examine the importance of canopy and soil disturbances in the establishment of edge vegetation." Samples of the soil seed bank along the future edge were taken, and seed germination in response to increased light, seed germination in response to soil disturbance, and the height growth of advance regeneration were all monitored. Relevant data included: most common species and germinated seeds from disturbed and undisturbed plots and seedling density, and recruitment, mortality, and total seedling survival on the forest edge and interior. Main conclusions were that "the large number of seeds of light-demanding species that germinated in response to soil disturbance and the germination bioassays confirm that lateral light penetration was adequate to promote seed germination of secondary species along forest edges, and that soil disturbance is not a necessary consequence of edge creation, but the disturbed soil experiment corroborates the importance of soil disturbance in the germination of buried seeds of some secondary species." Other canopy-related variables of soil (e.g., temperature fluctuations, concomitant changes in soil moisture) may also promote seed germination.

- *Variables*: soil moisture, canopy openness, seed germination, seed recruitment

Williams-Linera, Guadalupe. 1990b. "Vegetation Structure and Environmental Conditions of Forest Edges in Panama." *Journal of Ecology* 78(2): 356–73. doi: 10.2307/2261117.

The study sites were five clearings next to undisturbed forests in Panama. The pastures were created by cutting down forest and burning the area the following month before planting a crop with the first rain. There was no fire damage to the edges of the forest. The forest was described as tropical premontane wet forest, and the aim of the study was to investigate "the effects of newly created forest boundaries on environmental conditions and the structure of tropical vegetation from Panama." Data included:

changes in the percentage of canopy openness with distance from the edge, changes in density and basal area with distance into the forest, changes in life-form proportions of woody plants, and number of dead trees in strips parallel to the forest edge. Results indicated that as distance from the forest interior increases, the average temperature increases, the humidity decreases, and the canopy cover decreases. Also, the density and basal area of woody plants decreases and the stem density of woody plants was an average of 50% less in the forest than at the edges. Dead trees also increased with proximity to the edge, which indicate that "these results strongly suggest that there is an increase in tree mortality when an edge is created."

- *Variables*: temperature, humidity, vegetation, tree mortality

Young, Andrew, and Neil Mitchell. 1994. "Microclimate and Vegetation Edge Effects in a Fragmented Podocarp-Broadleaf Forest in New Zealand." *Biological Conservation* 67(1): 63–72. doi: 10.1016/0006-3207(94)90010-8.

The study site was a 200–250 ha plot in the Rodney Ecological District on the North Island of New Zealand. The forest plots are severely fragmented after heavy clearing for farming in the early 1900s. Five sites were monitored, and the dominant vegetation primarily included: *Beilschmiedia tarairi*, *Agathis australis*, *Leptospermum scoparium*, *Cyathea* sp., and *Dicksonia*. The study aimed to "(1) quantify the microclimate of forest edges and forest interior, (2) examine the vegetation composition and structure associated with these edges and interior microclimate regions, and (3) investigate how the importance of forest edge changes with fragment size." Data included: seasonal microclimate profiles; vegetation documentation including species, size, and density; and forest/edge comparisons of population structures. Results indicated that distinct microclimate gradients exist for south-facing edges for part of the year, but that these gradients (except for PAR) might break down over the winter period so that conditions in pasture are comparable to conditions in the forest. Additionally, the article identified three microclimate zones: "(1) an outer edge 10-m deep where PAR, air temperature, and VPD all decrease; (2) an inner zone which extends to approximately 50 m into the forest where air temperature and VPD continue to decrease but PAR has stabilized;" and (3) an interior zone where all three variables remain at constant levels.

- *Variables*: air temperature, vapor pressure deficit, and photosynthetically available radiation

Zulkiflee, Abd L., and George A. Blackburn. 2010. "The Effects of Gap Size on Some Microclimate Variables during Late Summer and Autumn in a Temperate Broadleaved Deciduous Forest." *International Journal of Biometeorology* 54(2): 119–29.

The study site was in northwest England, in a mixed, temperate, broadleaved deciduous forest. The dominant species were *Quercus petraea, Fagus sylvatica*, *Fraxinus excelsior*, and *Acer pseudoplatanus*. The study focused on recently created gaps of a variety of sizes, and the objective was to "analyze the effects of gap creation and variations in gap size on solar radiation, air temperature, soil temperature, relative humidity, wind speed, and soil water content, in terms of their overall characteristics and diurnal patterns." Relevant data included: physical and historical characteristics of four naturally created gaps, and statistical analysis of microclimate variables and soil moisture. Results indicated that there was a significant effect of gap size on solar radiation, and that larger gaps had much more rapid radiation changes than smaller gaps. The maximum air temperature at the center of the gaps was significantly different between gaps of different sizes, and the same trend was seen in average and maximum soil temperatures. Generally, solar radiation, air temperature, soil temperature, and soil water content increased significantly with gap size.

- *Variables*: solar radiation, air temperature, soil temperature, relative humidity, wind speed, soil water content

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
September 2014

2. REPORT TYPE
Final Report

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Forest Microclimate Characteristics Review: An Annotated Bibliography

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
21 2020 622720896

6. AUTHOR(S)
Rosemary Keane, Hannah Pitstick, Patrick J. Guertin, and Dick L. Gebhart

5d. PROJECT NUMBER
P2 #335114

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL SR-14-8

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Assistant Secretary of the Army
for Acquisition, Logistics, and Technology
1400 Defense Pentagon
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
ASA(ALT)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army owns many acres of forested training lands. Management of these forest lands can impact the Army's ability to meet training goals as these lands have implications to noise mitigation and threatened and endangered species populations. To support the need to manage these forested areas, the Environmental Processes Branch of the US Army Engineer Research and Development's Construction Engineering Research Laboratory conducts ongoing studies of forest lands, including the possible implications of climate change on forests. An important subtopic of that study is the microclimate a forest creates under and within its canopy; a forest microclimate can affect a wide variety of factors within the forest including how sound travels, vegetation regeneration, and faunal interactions. This report supports that important subtopic by creating an annotated bibliography of works related to how microclimates varied within forests and how they impacted environmental components within the forest. The resulting information will provide insight on how to design future work to capture relevant data and how to interpret those results.

15. SUBJECT TERMS
bibliography, forest land, land management, microclimate, climate change

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified	UU	91	